

CHARACTERIZATION OF TILLAGE PANS
IN SELECTED COASTAL PLAIN SOILS

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INTRODUCTION

Tillage pans are being recognized in many Coastal Plain areas, particularly in coarser textured soils. These pans result from compaction and cementation. In addition, some soil series are morphologically differentiated by the presence of a fragipan or spodic horizon. Whereas either of the latter types of pan are visually evident in examining a profile, the tillage pan is not identified by a change in morphological characteristics. Commonly, roots of field crops such as corn, cotton, soybeans, and alfalfa fail to penetrate tillage pans and either grow horizontally just above the pan or abort in the pan itself. This feature is useful in identification of the presence of a tillage pan. More importantly, such root systems indicate that the crop is prone to injury by drought. In those years when rainfall distribution is adequate, root restriction by tillage pans may have much less effect on the yields than in years when the soil becomes dry above the tillage pan. Such drought injury arising from the presence of a tillage pan is recognized by some farmers.

There exists the hazard that the tillage pan will adversely affect plant growth and reduce crop production. Destruction of the pan requires, logically, suitable deep plowing of tillage equipment be used to destroy the pan. Cost of this land renovation and the economic benefit are presently uncertain. The initial step to the problem is to recognize the cause of the pan formation. After obtaining this information, the methods for destroying the pan can be devised and tested. Land

renovation of this type aims at correcting this condition for a period of several years.

The principal objective of the present study was to determine which soil properties were altered in the tillage pan compared to the adjacent layer above or below the pan and at similar depths in adjacent virgin soil within the same mapping unit. Within this objective information was sought on field characterization of the pan and on the nature of the cementation and micromorphology. A secondary objective was to study the effect of the tillage pan on the distribution and morphological characteristics of roots of certain agronomic crops.

LITERATURE REVIEW

Current Interest in Soil Compaction

According to a report by the American Society of Agriculture Engineers in 1958 (3), investigators in twenty-one states and several Canadian provinces were actively engaged in soil compaction research. This report was indicative of the widespread occurrence of soil compaction and the significance attached to its effect on agriculture production. Attention to soil compaction problems has not been limited to North American workers. A number of German and Austrian workers have emphasized the need for identifying and correcting structural problems (17). Much work has been done on soil compaction related to road construction and no attempt is made here to review this phase of the literature. Many workers have studied pan formation, but little information has been obtained about the characteristics of tillage pans. Early field studies (111) indicated the existence of a plowsole or tillage pan in certain areas of Florida, but such studies did not explain how these pans developed.

Pan Classification

Illuviated clay layers and strongly compacted or indurated horizons occurring in soils are called pans. Raney, et al. (79) classified pans as induced or genetic. Induced pans are compacted layers which have resulted from recently applied compacting forces. These horizons of high

bulk density and low permeability most commonly occur just below the zone disturbed by normal tillage operations. Genetic pans are horizons that limit root and water penetration and have developed through the slow, but long continued action of soil genetic processes.

Genetic pans are subdivided according to their horizon characteristics into clay pans, fragipans, indurated pans, alkali soil pans, and organic pans (spodic horizons).

Clay pans are compacted horizons or layers rich in clay and separated from the overlying horizon by a more or less abrupt textural change. The abrupt textural change requires that the clay content must double or show an increase of 20% or more within a 3-inch vertical distance (100).

Fragipans are loamy subsurface horizons with a very low organic matter content, but much higher bulk density relative to the upper solum. When dry these pans are seemingly cemented and have a hard or very hard consistence; when moist they have a moderate or weak brittleness. Fragipans generally have abrupt or clear upper boundaries at depths of 15 to 40 inches below the original surface. They vary between a few inches and several feet in thickness (100).

Indurated pans tend to exhibit properties that are independent of the moisture content in the soil profile. This provides a valuable criterion for distinguishing cemented hardpans, induced pans, and fragipans (79).

Alkali soil pans occur in arid regions as impervious zones in soil profiles. In these pans, root and water penetration is limited by a layer of low permeability associated with the presence of high free alkali, usually Na salts (79).

Organic pans (spodic horizons) are illuvial accumulations of free sesquioxides associated with appreciable amounts of organic carbon. Certain of these pans exhibit illuvial accumulations of organic matter and amorphous silicates (100).

Pan Formation

Many agents or factors have been attributed to the development and occurrence of pans in soils. Some of the contributing causes of pan formation will be reviewed in the following order: iron, aluminum, silica, amount and type of clay, and compaction.

Iron

Iron has been suggested as a cementing agent for many years. Hilgard (43) attributed the formation of hardpans to the solution of materials at the weathering surface. Subsequently these solutions penetrated the soil to a depth where evapotranspiration occurred. Occupation of pores with air probably caused the accumulation of dissolved matter. Mudge (71) regarded the reduction of iron salts by organic acids to a ferrous state and oxidation to ferric salts through the action of air with subsequent precipitation in this form as a more acceptable theory for hardpan formation than the theory proposed by Hilgard.

Pan formation was explained by Morison and Sothers (70) as the formation of a sol of ferric hydroxide and humus. This sol, on reaching the groundwater table level, accumulated and during the dry season was deposited as an irreversible gel. This latter process could also take place through the action of electrolytes. These authors further stated that after the accumulation process began, a rapid increase in the amount of deposits occurred year after year until a hardpan resulted.

Under wet conditions the coagulated and desiccated colloids did not resuspend. They also stated that it is conceivable that some iron bacteria were involved in pan formation, since this layer usually held enough moisture for their existence. Possibly the organisms used humic acid combined with iron as a source of energy and left the iron in the form of ferric hydroxide. In studies conducted in the Yosemite Valley, Swinnerton (103) stated that iron bacteria, among many other forms, may be important factors in sand and gravel cementation.

In an early classification scheme of Florida soils, Sellard (96) supported the theory that hardpans were formed when humic acid from surface organic matter reduced iron compounds to soluble ferrous materials which were leached downward to the water table by percolating water. The ferrous humate oxidized to the ferric form during dry periods resulting in a cementing action on soil particles. Jenny and Smith (50) showed that a clay pan could be formed in a coarse grained system such as sand or glass beads if an electropositive iron sol and clay suspension were allowed to percolate alternately through the system. They also demonstrated that if humic colloids were mixed with the clay, no pan was formed.

A chemical composition study by Hanai (41), which concerned hardpan beneath a black volcanic ash soil in Japan, revealed no free silica; however, nearly 20% of the total Al and Fe existed as the free oxides. Drosdoff and Nikiforoff (24) found that some concretions contained a much higher percentage of Fe and Mn than the whole soil.

Clark, et al. (20) working with a soil from British Columbia reported that iron and aluminum oxide tended to accumulate in horizons containing concretions. They indicated soil particles were cemented

into hard ferruginous aggregates at a depth of 2 to 13 inches and both the inorganic and organic exchange sites were inactivated by the process.

In their work on the hardpan of a San Joaquin Valley soil, Nikiforoff and Alexander (72) concluded that cementation of soil particles by Fe and Si was responsible for hardpan development.

Studying the relation of free Fe and soil aggregation, Lutz (65) reported that there was a high positive correlation between the free Fe content and the degree of aggregation of silt and clay. He concluded that free Fe is an important factor which influences physical soil properties.

Aluminum

Martin and Reeve (67) reported in their work with an extract from the B horizon of a Podzol that maximum precipitation of both Al and humus occurred between pH 4.0 and pH 5.0. They also stated that C/Al ratios of less than 12 are probably facilitated by polymeric hydroxy forms of Al containing a number of positively charged exchange sites. They found that below pH 3.5 organic sol was flocculated by trivalent Al. Work on Podzolic soils in Scotland by Romans (86) noted the importance of organic matter as a podzolization mechanism. He stated that the breakdown of clay minerals under acid leaching conditions could be expected only after accumulation of humus. He contended that after a further considerable lapse of time that differential downward movement of aluminum and iron compounds resulted in the development of the indurated B horizon.

Richardson (84) compared hardpan and non-hardpan soils of Florida and concluded that the hardpan was due to precipitation of dispersed organic matter and soluble Al. In his investigation of various

properties of Leon soils in North Carolina, McCracken and Weed (68) found a maximum of free Al in the organic pan layer and very little in the other horizons. They found only a trace of iron in the organic pan and adjacent horizons. Yassoglou and Whiteside (120) considered free Al as a possible agent influencing the induration of fragipans in northern Michigan soils.

Silica

Silica was postulated as a cementing agent by many workers. Marbut (66) suggested that hardpans in the Leonardtown soils may be cemented with silicates. A similar conclusion for hardpan formation in San Joaquin soils was made by Nikiforoff and Alexander (72). Krusekopf (56) suggested the weathering of highly siliceous materials with consequent formation of a silica cementing agent was responsible for the hardpans in soils of the Ozark region. Anderson and White (4) found a slight accumulation of soluble silica but not of organic carbon in soil fragipans which suggested that Si compounds were the cementing agent. In reporting studies of hardpan development in the Red and Yellow Podzolic soils of Tennessee, Winters (118) postulated that colloidal Si was the major cementing material. He concluded that since the pH of the pan is usually as low as or a little lower than that of any of the upper horizons the precipitation in this layer of iron or aluminum from downward percolation water, was not favored. Light yellow and gray colors predominate in the pan which makes it unlikely that oxides or organic matter are the cementing agents. He noted that exposed surfaces in the very gray pans had a powdery appearance which was similar to the small concentration of secondary silica in other soils.

Knox (55) working with soils in New York concluded that colloidal silica in the Rockaway soil contributed strength to the fragipan. He observed that the removal of silica clay and hydrous oxides of Fe and Al weakened but did not destroy soil clods whereas the removal of colloidal silica from clods caused them to disintegrate. He noted that air-dry clods did not slake in water, but removal of colloidal silica from the clods made them slake in water.

Clay

In their study of fragipan horizons, Grossman and Cline (40) found rigidity to be correlated with percentage of clay and concluded that clay was the principle binding agent among primary particles.

Knox (55) working with Albie and Wurstboro soils concluded that illite was mostly responsible for the rigidity and strength of fragipans and was influential, along with colloidal silica, for the strength and rigidity of hardpans found in Rockaway soils. Bailey (7) working with soils containing fragipan horizons in Kentucky stated that these horizons generally contained more clay and correspondingly less silt than the horizon above the pan. In a study of fragipans occurring in some southern Indiana soils, Anderson and White (4) found that the clay of the fragipan horizon is low in montmorillonite by comparison with a similar soil profile without a fragipan. They stated that only a small amount of the montmorillonite present in the fragipan is capable of expansion under normal condition.

Tackett and Pearson (104) studied some characteristics of soil crust formation by simulated rainfall and found that the addition of 5% silt or clay to sand resulted in no measurable increase in crust strength. Increasing the silt content to 22.6% caused a sharp rise in

crust strength and a further 4% increase in clay nearly doubled the crust strength. Lotspeich (64) reported studies of strength and bulk density of a compacted mixture of kaolinite and glass beads at different moisture levels. He indicated that when the clay content was less than 10%, the bulk density of all treatments remains less than 1.7 g/cc. For all clay contents greater than 10%, maximum bulk densities were 0.2 to 0.3 g/cc higher than that of mixtures with 10% clay or less.

Compaction

The problem of soil compaction has been recognized and discussed for many years by numerous workers.

Hilgard (43) observed that plowing for many years at the same depth resulted in a consolidated layer below the plow depth that resembled a natural hardpan. Russell (88) discussed what he called Vilensky's principle, which is a hypothesis based chiefly on the research of Russian workers. This hypothesis stated that a moisture content exists for optimum crumb formation and that crumbs formed at this moisture content have maximum stability. This moisture content is near the sticky point. This hypothesis further proposed that particles subjected to stress at the optimum moisture content can be subjected to close packing which orients the clay particles thereby producing maximum binding.

The evaporation process and its three successive stages have been reviewed and discussed by Hide (42) and Lemon (60). Their investigations indicated that the first stage of moisture loss in soil is rapid and that this stage ended when a dry surface developed. The second stage exhibited a rapid decline in the rate of loss as the soil reservoir was depleted. The third stage of moisture loss occurred at an extremely slow rate. They proposed that close packing or orientation of

soil particles seemed to occur principally during the second and third stage of soil evaporation.

On the basis of laboratory work, Gerard, et al. (38) postulated that frequent irrigation followed by rapid evaporation or moisture absorption by plants, resulting in frequent wetting and drying cycles, contributed to a close packing of soil particles and subsequent pan formation. In a later study, Gerard (37) showed that factors such as moisture content, drying condition, texture, kind and level of exchangeable ions in the soil, and interactions of these factors significantly influenced soil strength and the moisture relationships. He concluded that the cohesive action of water molecules during slow drying, similar to the dispersion action of Na^+ , increased close packing of soil particles and the soil strength. Conversely, fast drying produced soil of lower strength due to the disruptive action of rapidly escaping water molecules on the arrangement of soil particles.

In a study of some physical and chemical properties of the hardpan or silt pan in various soils of West Virginia, Smith and Browning (98) concluded that the silt pans were not strongly cemented but their firmness resulted from the high density of packing and the complete lack of any effective aggregation. This conclusion was fully supported by the data of Nikiforoff, et al. (73). It has been concluded by Jha and Cline (51) that genesis of fragipans involved the physical phenomena of close packing through organization and orientation of clay in intergrain spaces. In his studies, Proctor (77) theorized that moisture acted as a lubricant which reduced the frictional resistance between soil particles and increased the amount of compaction for a given applied force until water fills the soil voids.

Vomocil and Flocker (113) in their studies with Yolo loam indicated that the compaction treatment may have resulted in changing the shape of aggregates from granular (near spherical) to platy. They hypothesized that for soils which have an initially granular structure and the principal cementing agent was a swelling clay, compaction reduced water-stable aggregates if it creates a platy structure by orientation of the clay. The swelling forces were more effective in slaking of aggregates when the clay particles were oriented parallel to each other.

Detailed studies of soil compaction by farm machinery have been conducted at the U. S. D. A. Tillage Research Laboratory at Auburn, Alabama. Weaver (116) found that the optimum moisture for compaction of Davidson loam closely approximated the optimum moisture content for tillage. He reported soil compaction by tractor tires to a depth of 9 inches, which is below the reach of normal tillage equipment. Jamison, et al. (49) observed that the compaction and moisture relationship of soils resulted from the compaction by tractor tires, was essentially the same as that predicted by Proctor (77). Steinbrenner and Gessel (101) studied the effect of tractor logging on physical properties of some forest soils in southwestern Washington. They reported that the soils from a cut-over area where a tractor was used, had a 35% loss in permeability rate, a 2.4% increase in bulk density, and a 10% decrease in microscopic pore space when compared to unharvested areas. The tractor road showed a 93% loss in permeability, 15% increase in bulk density, and 53% loss in microscopic pore space. Klute and Jacob (54) found a higher bulk density and lower percentage of air-filled pores in the soil subjected to tractor wheels. Russell, et al. (90) also found a higher density in the spray wheel middles than in the non-wheel middles; however, in areas containing a high content of organic matter less compaction was

found. Free, et al. (33) studying the compactability of certain New York soils in relation to organic matter content, found that one trip with an empty farm truck when the soil moisture content was 23% increased the bulk density from 1.32 to 1.50. At a soil moisture content of 17% four trips increased the bulk density from 1.24 to 1.58. Compared to mineral soils, soils with high amounts of organic matter were compacted to a lesser degree by the same force at a constant moisture content. Smith, et al. (99) reported that a soil with 2.9% organic matter, when worked repeatedly with heavy machinery, was found to have considerably higher bulk density than that of the underlying subsoil. They suggested that as a general rule, when the bulk density of the pan was similar to that of the subsoil below, there was a moderately compacted pan. When the bulk density of the pan was substantially greater than the subsoil density, severe compaction existed.

Vomocil, et al. (114) used infiltration rates as an index of compaction. They showed that increases in drawbar load and reduction of speed both increased the degree of compaction at three different levels of moisture content. Alternating soil moisture content affected compaction more than changes in speed and drawbar load.

Monovalent salt effect

Use of poor quality water (high sodium content and application of sodium nitrate and ammonium sulfate) have been reported as a factor for poor physical conditions. Gerard, et al. (39) found a high correlation between exchangeable sodium and soil strength as evaluated by modulus of rupture analysis. In connection with an irrigation experiment, Huberty and Pillsbury (44) indicated that both sodium nitrate and ammonium sulfate reduced the infiltration rate. In the same experiment horse manure and gypsum increased the infiltration rate compared with untreated soil.

Aldrich, et al. (1) investigated the effect of long term application of sodium nitrate and ammonium sulfate on soil infiltration rates. They suggested that the reduction of water movement caused partly by a reduction in micropore space resulting from partial structural breakdown.

Richardson (83) reported various physical and chemical properties of the hardpan. He attempted to produce a hardpan in the laboratory by various leaching techniques and found impervious conditions when soils were Na-saturated in the alkaline range.

Pan Effects on Plant Growth

The compacted zone may significantly affect the growth of plants and crop yields by reducing permeability of the soil to air and water thereby restricting plant root activity and nutrient uptake. Fountaine (31) stated that degraded soil structure affected plant growth through its effect on soil-water, soil-air, soil-heat relation, or through its effect on mechanical impedance of a soil.

Locke and Mathews (63) found that water from a infiltrometer penetrated the plowpan layer at the rate of about 0.2 inches per hour. However, when the plowpan layer was removed and the infiltrometer was set on the soil immediately below it, the rate increased to nine inches per hour. In studying a pasture soil compacted by animals, Federer, et al. (26) indicated that even on well managed pastures animal traffic can produce a significant decline in yield. He stated that reduced yields could be due to the indirect effects of compaction on aeration and moisture.

In their work with an artificially compacted soil, Rosenberg and Willits (87) found an increase in bulk density from 1.3 to 1.6 g/cc in a

sandy soil resulted in a 50% increase in the yield of barley. This was correlated significantly with a linear increase in available water. On a silt loam soil, they reported a 37% decrease in barley yields when the bulk density was increased from 1.30 to 1.65 g/cc by compaction. This response was correlated with O_2 diffusion. Raney, et al. (80) obtained increased cotton yields in dry years by deep plowing on medium-textured Mississippi River alluvial soil. However, no beneficial effect of deep tillage was reported when ample moisture was available. Locke, et al. (62) in investigating plow or tillage pans in a large area, reported that these pans hindered root penetration, reduced infiltration of water, increased erosion, and reduced crop yields.

Soil porosity

Baver (9) noted that plant growth ceased where the pore space was 10% of the soil volume. Flocker, et al. (29) studied the effect of soil compaction on the growth of tomatoes. They found optimum growth occurred in soils having 30 to 35% air space and that growth sharply declined when the air space was reduced to 10% or less. They stated also that for each soil there was an optimum air space for plant growth that was obtained when compression raised the bulk density slightly above the natural density of that particular soil. They concluded that a small amount of compaction in certain soils may be favorable to increased plant growth, flower bud formation, and seed germination. Additional compaction was detrimental.

Root penetration

Wiersum (117) suggested that plant roots growing into a rigid system were only able to penetrate pores that had a diameter exceeding

that of the root tips. Taylor and Gardner (106) showed that cotton roots readily grew into and through several centimeters of wax. This wax was not a truly rigid substance even though it was not porous.

Much attention has been given to root restriction by tight soil layers. Results of two experiments in Amarillo fine sandy soil by Taylor and Burnett (105) clearly showed that soil compaction altered the rooting pattern of cotton and other plants. They indicated that soil strength and not other physical factors (soil water relation, air porosity, aeration, and soil temperature) controlled the growth of roots through the moist soil. When the penetrometer measurement of soil strength reached 25 to 30 bars at field moisture capacity, roots failed to penetrate the soil mass whereas they grew through a similar soil having a strength of 19 bars. In a later study, Taylor, et al. (107) reported that the percentage of root penetration through cores of five different soils decreased curvilinearly with an increase in soil strength, and that no roots penetrated the cores when the strength was greater than 25 bars regardless of the soil material tested. Zimmerman and Kardos (122) found a highly significant negative correlation between bulk density of several soils and root weights of both soybean and sudangrass; in these soils, however, sudangrass roots penetrated the compacted soil more readily than did the soybean roots. In two soils they reported that at bulk density values of 1.8 and 1.9, the root penetration ceased.

Results of an 8-year study of sugarcane root development on 72 soils with bulk densities varying from 0.5 to 1.92 were reported by Trowse and Humbert (109). These workers found the root distribution was slightly reduced where the bulk density of the soil was in the range from 1.12 to 1.25; more pronounced effects on this distribution was observed where bulk densities were in the range of 1.36 to 1.46. Upon

examination of the branching of rootlets, a tendency toward angular turning and slight flattening was noted where root distribution was first affected and rootlet distortion was more pronounced with further increase in bulk density to 1.36. At bulk density of 1.46, root penetration was reduced seriously. However, the critical bulk density was reported to be 1.52 or higher.

Veihmeyer and Hendrickson (110) noted that the soil density above which roots do not penetrate is not necessarily the same for all soils. They reported that roots of sunflower were not found at densities of 1.9 or above and in some cases there was no root penetration at densities of 1.7 to 1.8 in coarse textured soils. On the other hand, there was no root penetration in fine-textured soils when the density reached values 1.6 or 1.7. The lowest density into which roots failed to penetrate was 1.46 which was obtained with Aiken clay soil. Bertrand and Kohnke (10) reported that subsoil with an initial bulk density of 1.2 was more favorable for corn growth than the same soil which has been compacted to a bulk density of 1.5. In their studies, different rates of compaction caused a greater difference in the quantity of top growth than root growth. They further indicated that, in very loose subsoil with a bulk density of 1.2, the corn roots penetrated the subsoil to a depth of 21 inches at the end of five weeks. In dense subsoil, where the bulk density was 1.5, the roots penetrated only nine inches below the surface.

Flocker, et al. (30) reported that stands of Austrian peas, horse bean and purple vetch were significantly reduced by soil compaction. Stand estimates of three crops on severely compacted plots were reported to be only 62% of those plots not compacted. Yields of all the crops tested were reduced significantly an average of 24% by the compaction treatment.

Nutrient absorption

Any great reduction of soil aeration by compaction has been shown to create an imbalance in the nutrient absorption by plants. Several investigators (78, 61, 76, 102) have shown that plant nutrient uptake was reduced by restricting the O_2 supply or by high concentrations of CO_2 in the soil. Lawton (59) reported that the order of reduction in nutrient absorption by crops growing in nutrient solution under restricted aeration was $K > Ca > Mg > N > P$. He obtained similar results when aeration was restricted by reducing soil porosity through compaction. Bertrand and Kohnke (10) found that compacted subsoils significantly reduced the total amount of N and K in corn plants but no significant difference in P content was observed. Flocker, et al. (28) studied the influence of soil compaction on the P absorption. They reported that, when P was not added the fresh weight yield of tomatoes decreased as the density of soil increased. At rates of 44 and 88 pounds of P per acre, the growth of the tomatoes increased until the bulk density became the limiting factor at a value of 1.6; at this density or greater the P uptake was reduced.

Subsoiling Effects

Subsoiling studies

Attempts to correct poor physical condition of subsoils in many areas have met with varying degrees of success. Woodruff and Smith (119) reported that the effect of subsoiling was shown by significantly increased yields for the first three years but this response declined until no significant difference was found within six years. From their studies, they concluded that subsoiling improved the water intake and storage capacity as compared to the untreated areas. Research, conducted

in the Delta section of Mississippi (80), showed that subsoiling to break the tillage pan significantly increased cotton stand and size, increased the pore space, and reduced the bulk density. These effects disappeared the following year. They also reported that in years of less favorable moisture, shattering of a deep compacted layer increased seed cotton production. Patrick, et al. (75) obtained yield increases of both corn and cotton from deep tillage and deep fertilizer placement in Gallion silt loam. In 1954 and 1956, the increases were of the order of 20 to 25 bu of corn and 300 to 800 lb of seed cotton per acre. No significant increase in yield was obtained in 1955 from these treatments.

Garey and Brown (36) reported that chiseling and subsoiling were not of value in some Arkansas soils with compacted subsoils and which had poor aggregating properties. They observed that root restriction by the tillage pan was not a serious factor when fertility and water supply were adequate. Robertson, et al. (85) studied subsoiling effects in six different soils in Florida. They reported that when a spodic horizon existed, yield increases were obtained both for subsoiling alone and fertilizer placed in the subsoil. However, where tillage pans existed in the Norfolk, Ruston or Red Bay soils that they tested, a better response to subsoiling treatments was found only in years when droughts were of short duration. These workers observed that, in years when the drought period was of 25 days duration, the earlier advantage of subsoiling treatments in providing a deeper root system and a larger corn plant was lost from drought injury.

Soil Compaction Measurement

Penetrometers

Penetrometers, which are spring-operated devices, were designed to measure the force required to insert a probe of assigned area to an arbitrarily assigned depth in the soil. Various instruments were made for this purpose. The Proctor penetrometer was developed to provide quantitative measurements of soil penetration resistance. This constant load type of penetrometer has attained considerable acceptance and has been used under a wide range of conditions. Proctor (77) explained the operation of this instrument and some of its advantages and disadvantages. The American Society for Testing Materials (2) has proposed a procedure for determining the resistance of soils using the Proctor penetrometer. Another widely accepted instrument, termed the pocket penetrometer, was devised for hand operation and was calibrated to read in kg/cm^2 . This instrument was described by Davidson (23).

Penetrometer measurement

Russell (89) stated that the penetrometer can be used in studying properties of soils and in the investigation of soil crusts, plowpans, or other compaction phenomena. Richards (82) has described a penetrometer and has shown that readings are affected by the presence of plant roots, soil moisture, and compacted layers in the soil.

Scott - Blair (95) has proposed that compressibility be used to determine tilth. He found that the more a soil can be compressed, the better is the tilth or looseness of the soil structure. Black (11) reported penetrometer measurements were useful in evaluating soil structure.

Penetrometer interpretation

Interpretation of penetrometer measurements has required considerable studies. Reed (81) used the force of penetration to indicate the compactness of a soil. However, Culpin (21) concluded that soil compactness was only one of many factors which influenced consolidations. He stated that resistance of the soil to penetration gave a measure of the state of the consolidation although this resistance was the integrated effect of several physical factors such as soil cohesion, plasticity, and surface friction between the soil and the probe. Bradfield and Jamison (14) characterized soil structure from penetrometer data and pore distribution curves.

Shaw, et al. (97) presented the results of four years of experience in the use of a soil penetrometer. They studied the nature and extent of physical changes in the profiles of typical Ohio soils. They were trying to determine the effects of different methods of soil management and water applications upon the physical characteristics of the soils. They stated that soil moisture seemed to be the dominant factor that influenced the penetrometer readings. However, there was not a simple relation between these readings and the soil moisture. They found that the zone of maximum compaction moved nearer to the surface as the number of tillage operations increased. They concluded that penetrometer readings were useful in diagnosis of soil compaction but not of specific soil properties.

Soil Micromorphology

Thin section preparation

Thin sections of soils have made it possible to examine microscopically the soil constituents in their natural, undisturbed arrangements.

Several soil scientists and geologists used thin section technique to study soil in the years from 1920 to 1930. However, they were handicapped by the lack of suitable impregnating media. The first fairly satisfactory method for the preparation of thin sections was given by Kubiena (57). Natural resins and plastic have been used for the impregnation of specimens; plastic that polymerizes at room temperatures or under outdoor conditions was used successfully. Most of the methods now in use are modifications of the procedure described by Bourbeau and Berger (13).

Petrographic microscopy

Several workers have studied the micromorphology of soils using the petrographic microscope. Brewer and Haldane (16) used an experiment with the movement of clay suspension in sand columns to show that clay will orient strongly in a definite manner on the surfaces of sand grains. They also produced oriented coatings around sand grains by immersing the sand columns in clay suspensions and then blowing hot air over the surface to enhance the capillary movement. In this study they found that the presence of a large amount of silt had a disrupting effect on the orientation of the illuviated clay.

Profiles of some New York soils were examined by Frei and Cline (34). From thin sections, they found evidence that the loss of clay from upper horizons and its accumulation in the lower horizons resulted from the action of water. They noted that the clay was not uniformly distributed through the soil but was concentrated on the aggregates. These workers reasoned that if the clays were the weathering product of primary minerals in situ, then they should be uniformly distributed throughout the soil. They considered that the layering and orientation

of the clay were unlikely to result from residues of other minerals. They concluded from the optical continuity and mode of occurrence of the clay skins that the clays were deposited by percolation.

Tackett and Pearson (104) examined petrographic thin sections prepared from the crust of B₂ horizons exposed to rainfall. They noted that the exposed surface was coated with a thin clay skin. Further orientation of the clay was not found after the soil samples were subjected to compaction. They observed also that within a few millimeters of the crust surface both the coarse grains and the finer matrix were very closely packed with no visible voids; this structure resembled that of a fragipan. They reported that, below the crust layer proper, the structure was different in that the fine sand and silty materials were clustered around the coarse particles and there were abundant voids which were the size of the sand grains.

Profiles of four soils were studied by thin sections in work by Arnaud and Whiteside (6). They observed accumulations of colloidal materials along the faces of peds, along root channels, and other voids. They suggested that illuviation of clay had occurred within the B horizon; the translocated clay displayed orientation parallel to the direction of the illuviation. McCracken and Weed (68) studied the micromorphology of pan horizons in several soils of the Southeastern States. In these studies, the Norfolk genetic pan layers and the Leon spodic horizon were similar in that both had a large number of intergranular bridges. They found that the Grenada fragipan and the Norfolk tillage pan have a relatively close packed fabric. The few clay concentrations were not oriented in these thin sections.

A thin section study of some soils of Northeastern Florida was made by Carlisle (18). He concluded that the oriented clay skins found

in the spodic horizon of the Leon soils were of pedogenic origin. He also indicated that a small amount of oriented clay had been redeposited along soil pores, and root channels in the fine-textured horizons; remnants of inherited oriented clay were also detected.

Johnston and Peterson (53) used thin sections in a study of soil pore space. They found less pores in the matrix from either illuviated horizons or pans than in other horizons. Clay disposition on the surfaces of pore spaces in the deeper horizons was evidence that the process of illuviation had been active.

Thin sections of soils have been used by Brewer (15) to study the mineralogy of cutans, especially in regard to the interpretation of their genetic significance. He described conditions for the identification of some Fe, Mn, and Al compounds.

METHODS AND PROCEDURES

Sampling Procedures

Selection of soil sites

Several Coastal Plain soils that occurred in North and West Florida were chosen for study. Soil survey reports of Gadsden, Washington, and Escambia Counties (108, 45, 19) were used as aids in the selection of probable sites containing suitable areas of cultivated and adjacent virgin soil having the same mapping unit. The soil maps with aerial mosaic background were examined and several paired sites were marked for inspection later in the field. The soil series selected for study were Norfolk, Lakeland, and Red Bay. Because the latter soil did not occur in Washington County, sites of Orangeburg soils were chosen also.

The field trip to inspect these sites was planned to follow a period of heavy rainfall. The first trip was made in January, 1965. The procedure was to inspect the tentative site. Where the virgin soil from the map had been cultivated, or recently cut for timber, the site was rejected. The nearest alternative site was inspected. If suitable, the soil series was confirmed both in the virgin and cultivated areas. As described below, pits were dug in the cultivated and virgin soil to enable soil measurements and soil samples to be taken.

In Gadsden County, the paired sites were obtained for three Red Bay, three Norfolk, and two Lakeland soils. In Washington County, one Norfolk, two Orangeburg, and two Lakeland soils were studied and sampled. In Escambia County, two sites of Red Bay, one of Norfolk, and two of

Lakeland soils were used. In Santa Rosa County, at the West Florida Experiment Station which had been mapped, one Red Bay and one Norfolk soil were selected for the paired comparison and sampled.

In June, 1965, after a period of heavy rainfall, some of these sites were revisited to examine root distribution with respect to compaction changes. The sampling procedure was essentially the same as that used at the earlier date except that root samples were also taken.

Selection of pit sites ✓

At the cultivated site, a Proctor penetrometer with a tapered probe was used to examine the area by probing the compacted zone, termed the tillage pan, for uniformity. The area selected for the pit was considered representative of the pan property and was 30 to 40 meters (m) from fences or the edge of the field but within 60 m of the virgin soil. The pit at the cultivated site was dug first, usually 1.5 m wide and 60 cm deep. The face of the pit was smoothed with a spade. Readings with the pocket penetrometer were taken at successive intervals of 3 cm down the profile. Changes in soil compaction were recorded and several such sets of readings were used to delineate the tillage pan and other changes in the compaction. Soil depths above, in and below the tillage pans were recorded with the corresponding penetrometer readings. The samples for thin sections, bulk density, and soil analysis were taken as described below and the remaining soil replaced.

The corresponding, adjacent pit site in the virgin soil area was selected away from large trees or pathways. The pit was dug similarly to that at the cultivated site. Penetrometer readings were taken at depths corresponding to those where changes in compaction occurred in the cultivated soil. For comparative purposes, these depths are

expressed as above, in, or below the depth where the tillage pan was found in the cultivated soil. Sampling procedures were similar also.

Core samples

Samples for physical and chemical soil analysis were taken with a double cylinder, hammer-driven core sampler as described by Blake (12). This device was driven horizontally into the soil until the inner cylinder was filled with the soil. The inner core was separated and trimmed flush with the cylinder. The soil core was transferred to a polyethylene bag which was labelled and sealed for transport to the laboratory. Such samples were obtained with respect to the penetrometer readings so that they were representative of soil above, below, or in the tillage pan. The virgin soil was sampled similarly at the corresponding depths.

Thin section samples

A circular metal dish 6 cm in diameter and 2 cm deep was pressed or driven with a mallet into the soil. Sampling positions were similar to those for the core samples. Each dish was marked for orientation and location and capped for transport to the laboratory.

Root samples

After the pit was dug, the tillage pan was located by the penetrometer readings. Bulk samples of soil above, in, and below the pan were taken and placed in plastic bags. Selection of these samples was made so that, where possible, continuous root systems were represented. Where roots failed to penetrate the pan, roots above the pan were taken and those on or in the upper portion of the pan. Bermudagrass, Pensacola bahiagrass, corn, cotton, and soybean roots were studied as they occurred at the field locations.

Physical AnalysisBulk density

The soil core sampler yielded a cylinder of soil 5.35 cm by 6.00 cm. Weight of this soil in the polyethylene bag was determined. The soil was mixed in the bag and 25 g taken, placed in a tared dish, dried at 105C overnight, and weighed. The weight of the damp soil was obtained and expressed as oven-dry weight for the entire core using the oven-dry weight of the smaller sample for the computation. The bulk density was determined by dividing the oven-dry weight of the core sample by the volume of the sample.

Particle density

A representative portion of the soil core, approximately 10 g was placed in a tared 50-ml volumetric flask. The flask and soil were dried at 105C to constant weight which was obtained usually after 12 hours of drying. Each flask was then one-half filled with distilled water, shaken vigorously, and let stand for an hour. The entrapped air was removed by suction. After the air bubbles ceased to be seen, the volume was brought to 50 ml with distilled water and the flask weighed. A tared flask was used to determine the weight of 50 ml of the water at the room temperature. The average particle density was calculated by dividing the weight of the dry soil by the weight of the water displaced. The method is a slightly modified version of the standard pycnometer method (112).

Pore space

The pore space or total porosity was calculated using the ratio of the bulk density of the soil core to the average particle density and subtraction of this from unity. The percent pore space was obtained by multiplying this value by 100. The method followed that given by Vomocil (112).

Particle size distribution

Soil remaining from the air-dried core samples was passed through a 2-mm sieve. Some samples required crushing with a wooden roller prior to sieving. Roots and concretions were discarded in the screening process. Depending on the coarseness of the soil texture 10 to 40 g of the soil were weighed into a 250-ml beaker for analysis of particle size distribution. The organic matter was destroyed by adding 10 ml of 30% hydrogen peroxide at hourly intervals and heating gently. The soil was transferred to a polyethylene tube of 100 ml capacity using a jet of 5% sodium chloride for the transfer. After centrifuging, the clear supernatant solution was saved for later analysis. The soil was washed once more with 50 ml of the salt solution and transferred from the tube to a cylinder fitted with a 300-mesh sieve. The fractionation of sand, silt, and clay followed procedures given by Kunze and Rich (58) except that a dispersing reagent was not used and essentially a Na-clay was obtained. The silt fraction was washed with a very dilute sodium hydroxide and, after centrifuging, any remaining clay was added to the main clay suspension. One-half of the clay was taken for differential thermal analysis (DTA) and dried at 50C. This weight was used for the clay content calculation; dry sand and silt weights were also obtained and the appropriate calculations made to obtain these contents in the air-dried soil.

Differential thermal analysis

Clays previously separated for particle size distribution were dried at 50C for a period of a week. Each sample was ground coarsely in an agate mortar. A 150-mg portion was taken and mixed with 225 mg of asbestos which had been fired at 1000C and passed through a hammer mill fitted with a fine screen. This mixture was then ground in an agate mortar until visually homogenous, a process taking less than a minute. The mixture was transferred to one of the four sampling positions in the insert holder for DTA apparatus and gently tamped into place using the packing tool. The remainder of the mixture, usually about 50 mg, was removed and weighed. In the paired reference sample holder, the fired asbestos was tamped similarly. Standard clay minerals were run in a similar manner as that above for the soil clays. Four pairs of DTA comparisons were used in this Deltatherm nickel assembly. Each pair was connected to a transistorized circuit and run at 25% sensitivity using a heating rate of 10C per minute, from 25C usually to 800C. Endothermic reaction in the 50-150C, 280-330C, and 525-600C regions were measured by a planimeter. These readings were expressed as percentage of the total endothermos.

X-ray diffraction patterns

A portion of clay suspension which was subjected previously to the dithionite and sodium hydroxide extraction, as described below, was saturated with calcium chloride. The suspension was washed with distilled water until it became chloride free. A few drops of 25% ethylene glycol were added to the suspension and a small portion of this suspension was transferred to a clean petrographic slide. The sample was allowed to dry at room temperature without disturbance to obtain the maximum orientation of the clay particles.

The prepared clay slides were processed for the X-ray-diffraction patterns using a Phillips Norelco diffractometer with Cu K α radiation and a Geiger tube detector. Operating conditions for this instrument were a current of 10 ma at a setting of 10 kv with 1500 v on the Geiger tube. The scanning speed was 1° per minute and the chart speed was 2.5 cm per minute. The 2θ angles were converted to angstrom units (A) with the aid of graphs and charts prepared by Parrish and Irwin (74). The X-ray instrument was calibrated using the 3.35A line of quartz as the standard. The presence of gibbsite, kaolinite or halloysite, vermiculite, montmorillonite and quartz was sought.

Petrographic microscopy

Certain of the samples taken for thin sections were selected for study. The soil was impregnated with glyptal and sent to a laboratory operated by Rudolf von Huene. The vertical thin sections were made with modifications of the technique developed by Bourbeau and Berger (13). These were examined in our laboratory with the aid of a petrographic microscope for packing density, clay orientation and pore space. Photomicrographs were taken from the thin section slides by a single lens reflex camera attached to the microscope. Exposure time was set at 1 second, using Kodachrome II film. The light intensity was adjusted by maintaining a 5.5 voltage. The photomicrographs were taken under crossed polarized light with a magnification of 25.

Chemical Analysis

Organic matter

Soil organic matter content was determined by wet oxidation using a slight modification of the Walkley-Black method (115). The weight of

air-dried soil from the core samples was 1 to 2 g. O-phenanthroline was used as the indicator of the titration of the dichromate with a standardized ferrous sulfate solution.

Citrate-dithionite extraction /

The method for the removal of free iron oxide was essentially the same as that described by Jackson (46). A representative aliquot of the clay suspension, taken to obtain 0.5 to 1.0 g of clay, was transferred to a 100-ml polyethylene tube. Forty ml of 0.3M sodium citrate solution and 5 ml of 1N sodium bicarbonate were added to the sample in the tube. A series of these tubes was placed in a water-bath at 80C and 1.0 g of solid sodium dithionite was added to each. After 15 minutes of intermittent stirring with a polyethylene-covered rod, 10 ml of a saturated solution of sodium chloride were added to each of the tubes and stirred. The tubes were removed from the bath and the clay precipitated by centrifuging at 2,200 rpm for 5 minutes. The clear supernatant was decanted into a 500-ml volumetric flask. The clay was resuspended in 30 ml of 1M sodium chloride solution using a rubber-tipped stirrer run at high speed to achieve thorough mixing. The clay was separated by centrifuging. The supernatant was added to the previous extract of the sample. The combined extract was brought to 500 ml with deionized water and shaken well. Fifty milliliters of this solution were transferred to a plastic vial and capped for use in Fe, Al, and Si determinations. The clay was saved for further treatment. The reagent blank was made similarly.

Preliminary study showed that citrate interfered with the Al and Si determinations which are discussed elsewhere. Accordingly, 10 ml of the above diluted extract were pipetted into a Pt dish and taken to dryness slowly on a hot plate. The Pt dish was placed in a flat quartz crucible

and ashed at 700C for an hour. Upon cooling, 20 ml of 0.5N sodium hydroxide were added and warmed on the hot plate to facilitate solution of the Al and Si. The solution was cooled, adjusted with water to a 30-ml volume, poured into a plastic vial and capped for later Al and Si analysis.

Sodium hydroxide extraction

The clay remaining after the above citrate-dithionite treatment was heated to nearly 100C by placing the tubes in a boiling water-bath. Fifty milliliters of boiling 0.5N sodium hydroxide were added to the clay and stirred for a period of 2.5 minutes which is the recommended procedure for the removal of amorphous Al and Si according to Jackson (48). The tubes were removed and promptly cooled to room temperature. The clay was separated by centrifuging at 2,200 rpm and the clear supernatant was decanted into a plastic beaker. The clay was resuspended again in 20 ml of cold 0.1N sodium hydroxide containing 2% sodium chloride, stirred, and centrifuged. The clear supernatant was added to the previous extraction in the beaker. The volume was brought to 500 ml with deionized water and mixed by shaking. An aliquot of this solution was transferred to a 50-ml plastic vial and capped for later analyses. Contact time with Pyrex glassware was avoided so far as possible to minimize Si contamination. The reagent blank was also diluted to this volume and stored in plastic.

Acid ammonium acetate extraction

The air-dried sieved soil, either from the core samples or from samples taken for the root study, was extracted with ammonium acetate reagent which was 1N with respect to acetate and 0.7N with respect to NH_4^+ which gave a pH of 4.8 for the reagent. Five grams of the soil sample were shaken with 25 ml of this reagent for 30 minutes, and then filtered.

The filtrate was analyzed, as described below, for Ca, Mg, K and P.

Analytical procedures

Soil reaction -- Fifty grams of the sieved soil were mixed with 100 ml of distilled water. The mixture was stirred three times during an equilibrating period of 60 minutes. The sample was stirred just prior to reading the pH using a Beckman Zeromatic pH meter and glass electrode.

Aluminum -- The method of Yuan and Fiskell (121) was used to analyze Al in the extracts from the peroxide, citrate-dithionite, and sodium hydroxide treatments. A suitable aliquot of the soil extract was pipetted into a 50-ml beaker and acidified with 1N hydrochloric acid. Ten milliliters of aluminon reagent were added and brought to nearly 50 ml with distilled water. This solution was adjusted to pH 3.5 using 1N hydrochloric acid. The solution was heated to boiling; then it was removed and cooled. The volume was brought to 50 ml. A Model B Beckman spectrophotometer was used to measure the transmittance at 540 mμ using the reagent blank for the setting for 100%. The standard curve was prepared using 0, 10, 20, 30 and 50 ug of Al under similar conditions.

Iron -- The O-phenanthroline method for Fe given by Sandell (91) was used for Fe determination in the soil extracts. A suitable aliquot of the soil extract was pipetted into a 50-ml beaker and acidified with 1N hydrochloric acid. One milliliter of 1% hydroquinone solution and 1 ml of 0.5% O-phenanthroline solution were added and the volume increased to 30 ml with deionized water. The pH was adjusted to 3.5 using 0.3M sodium citrate. Then, the volume was brought to 50 ml and the sample shaken. After 30 minutes the transmittance was read at 508 mμ with the spectrophotometer. The reagent blank was set at a transmittance of 100%. The standard curve was prepared similarly using 0, 25, 50, 75 ug of Fe.

Silicon -- The sensitive silicomolybdate method for Si analysis reported by Schink (92) was chosen for determining the extractable Si removed by the peroxide, citrate-dithionite, and sodium hydroxide treatments which were discussed previously. These extracts were shaken well before pipetting a suitable aliquot into a polypropylene beaker. Thirty ml of deionized water were added and the sample mixed by swirling. One milliliter of the molybdosulfuric acid (0.2M ammonium molybdate in 0.66N sulfuric acid) was added, stirred with a plastic rod, and allowed to stand for 20 minutes for formation of the silicomolybdate complex. Fifteen milliliters of 18N sulfuric acid were added. The solution was transferred to a glass separatory funnel and 10 ml of ethyl acetate were added. The funnel was shaken for 1 minute and the phases allowed to separate. The aqueous phase was discarded and the organic layer was transferred to a 12-ml polyethylene tube. These tubes were centrifuged at 2,200 rpm for 2 minutes. The transmittance was read at 335 mμ in quartz cuvettes in the Model B Beckman spectrophotometer. A reagent blank prepared similarly was used to set the transmittance at 100%. The stock solution contained 1000 ppm of Si derived from sodium silicofluoride which was dissolved in deionized water and kept in a sealed polyethylene bottle. The standard solutions were made with 0, 2, 4, 8, and 12 ppm of Si in 0.1M sodium hydroxide. The standard curve for Si was prepared using the same volume and reagents employed for Si determination described for the soil extracts. From this curve and the dilution factors involved the microgram of Si per gram of clay were calculated. The acid conditions that prevailed when the glass separatory funnels or quartz cuvettes were used for the Si determination did not result in detectable amounts of Si being dissolved from these sources.

Flame emission analyses -- The Ca, and K in the acid ammonium acetate extracts of the soil were analyzed using an oxygen-acetylene flame in conjunction with the Model B Beckman spectrophotometer. The Ca emission line at 554 mu, and that for K at 768 mu were used to determine these elements respectively. Standards for Ca were 0, 50, 100, 200, 300, and 400 ppm in the acid ammonium acetate medium. Standards for K were 0, 20, 40, and 60 ppm in similar acetate medium. Soil Ca and K values were calculated using the appropriate standard curve and dilution factor:

The Mg analysis was made using a hydrogen-oxygen flame and Beckman DU spectrophotometer at a wave length of 285 mu. Standard solutions in the acid ammonium acetate contained 0, 50, 100, 150, and 200 ppm of Mg. The soil Mg values were obtained by comparing the Mg emission value of the soil extract to that of the standard curve and correction for the dilution factor involved.

Phosphorus -- The soil P extracted with the acid ammonium acetate was determined by the stannous chloride and chloromolybdate procedure given by Jackson (47). Five milliliters of the extract were placed in a 50-ml volumetric flask, 30 ml of water were added, 10 ml of 1.5% ammonium molybdate in 3.5N hydrochloric acid were added and 10 ml of 0.06% stannous chloride solution used to reduce the P to form the phosphomolybdate complex. The volume was brought to 50 ml and the flask shaken well. The transmittancy was measured in the Beckman Model B spectrophotometer at 660 mu. The standard curve was made using 0, 25, 50, and 100 ug of P in a 50-ml volume. The soil P was found from the standard curve and the appropriate dilution.

Root Sampling and Procedures

Sampling procedure

Sites chosen for the soil samples were used for root studies in these fields. These were inspected in June, 1965, after a period of intense rainfall. Pits were dug large enough to permit a study of the root distribution above, in and below the tillage pan. Observations on the penetration of the roots into the pan were taken. In cases where roots penetrated the pan, the roots above, in, and below the pan were taken separately, and placed in a polyethylene bag with the corresponding moist soil. These bags were labeled and transported to the laboratory.

The soil was washed from the roots using a spray of tap water. The roots were photographed immediately after washing. A portion of the soil was dried and sieved for analysis as described previously.

Root sectioning for microscopy

The young lateral roots were clipped from the main roots. Representative lateral roots were excised through the meristematic, elongation, and mature zones. Each zone was placed in a plastic vial and dehydrated into the sequence proposed by Johansen (52). The roots were fixed in paraffin and thin sections approximately 10 μ in thickness were cut by a microtome. The thin sections were transferred to glass slides where they were fixed and stained by Johansen's quadruple combination method (52). Cover slips were placed on the root thin sections. Photomicrographs of the root cross-sections were made where 100X and 430X magnifications were obtained with a light microscope.

Root analysis

A portion of the freshly cleaned roots, usually 5 g, was transferred

to a porcelain dish, dried, ashed for 30 minutes at 300C and 60 minutes at 600C in a muffle furnace. The ash was cooled; 20 ml of deionized water, and 4 ml of perchloric acid were added. This solution was evaporated nearly to dryness on a hotplate. Twenty milliliters of 1N hydrochloric acid were added and the solution transferred to a polyethylene tube and centrifuged the supernatant solution was decanted into a 50-ml volumetric flask and made to volume with deionized water. The insoluble residue in the dish was transferred to the centrifuge tube using a jet of water and a plastic stirring rod. The aqueous portion was decanted after centrifuging. The residue was treated with 50 ml of hot, 0.5N sodium hydroxide, shaken after stoppering, and the tubes centrifuged again. These supernatants were transferred to plastic vials and capped for later Si determination.

The solutions in the volumetric flask were analyzed for Fe, Al, Si, and K by the methods described for the soil extracts. An aliquot was diluted with 1000 ppm of a La solution and analyzed for Ca and Mg using a Model 303 Perkin-Elmer Atomic Absorption spectrophotometer and air-acetylene flame. Absorption of Ca was measured at 422.7 mu and for Mg at 285.2 mu. The results were interpreted from a standard curve prepared from the absorptions of known amounts of Ca in the range 0 to 40 ppm and Mg in the range 0 to 4 ppm. Results were expressed on the basis of the fresh root weight.

RESULTS AND DISCUSSION

Tillage Pan Characterization

Soil strength

Proctor penetrometer measurements -- Compaction of a soil was evaluated using the vertically applied pressure change found when the modified Proctor penetrometer was inserted into the soil. This instrument provided a preliminary identification of the depth at which a compaction change occurred and the strength of the compaction. By making several such probings, the existence of a tillage pan could be determined in the field and some measure of the uniformity of the soil strength gained. From experience obtained by several thousand such probings made at the West Florida Experiment Station, certain limitations in the usefulness of these values became apparent. Principal disadvantage was found to be the change in penetration pressure with changes in soil moisture. When the soil was dry, penetration into the tillage pan was not always possible even with the pointed probe. Another uncertainty was the factor of friction which increased with the depth of penetration. This made it difficult to estimate the thickness of the compacted soil layer. Because the soil being probed could not be seen, changes in texture or occurrence of plinthite were not recognized. The advantage found in using this probe was the saving of time and effort otherwise used where a pit was dug and a detailed study of the profile was made. When the Proctor penetrometer was used in a pit to take horizontal measurements, the instrument proved cumbersome but the data obtained were similar to that found with the pocket penetrometer.

Pocket penetrometer measurements -- Horizontal measurements of the soil strength or compaction were made with the pocket penetrometer. These were made, as described previously, on the smoothed face of the pit and under ideally moist soil conditions. These measurements made possible the delineation of the tillage pan in cultivated soils. The procedure permitted a detailed examination of the soil strength at the depth to which the soil had been cultivated and then had settled from the heavy rainfall. The average of many such readings taken at each site was taken for this horizon. Immediately below this zone, another zone of higher readings was found and these were often several times greater than that found in the horizon immediately above this one. This zone was subjected to many probings to decide at what depth the increased soil strength persisted and the average of these was recorded. Where a sharp drop in the pressure required to force the penetrometer into the soil was consistently found deeper in the profile, the depth of this change and the average penetrometer reading were recorded. The compacted soil found between the two layers of lesser soil strength, as determined by the penetrometer measurements, was designated as the tillage pan. The primary purpose of examining the nearby site of virgin soil was to confirm the lack of, or presence of, a similar compacted horizon to that found in the cultivated soil. Also, these data from the virgin soil sites served as a reference in evaluating the changes that had occurred with years of cultivation.

Soil strength comparisons -- The average soil strengths which were found in the 20 paired sites were evaluated as paired comparisons above, in, and below the pan. The average obtained for each soil series are shown in Table 1 and the range of the values that were obtained is also indicated. Details with respect to locations are given in Appendix

Table 1 -- Soil strength measurements by pocket penetrometer of Coastal Plain soils selected for the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|--------------------------------|---------------|----------------------------------|-------------|-------------|
| | | Above | In | Below |
| ----- kg/cm ² ----- | | | | |
| Norfolk | 6 cultivated | 1.12±0.62 | 2.90±0.75 | 1.58±0.50 |
| | 6 virgin | 0.75±0.25 | 1.35±0.85 | 1.33±0.67 |
| Red Bay | 6 cultivated | 1.58±1.00 | 3.63±0.50 | 1.75±0.05 |
| | 6 virgin | 1.13±0.78 | 1.54±0.25 | 1.71±0.29 |
| Orangeburg | 2 cultivated | 1.13±0.75 | 3.12±0.13 | 2.12±0.13 |
| | 2 virgin | 0.88±0.12 | 1.25±0.25 | 2.00±0.50 |
| Lakeland | 6 cultivated | 1.21±0.79 | 2.63±0.87 | 1.08±0.90 |
| | 6 virgin | 0.67±0.33 | 0.75±0.50 | 0.54±0.21 |
| Average | 20 cultivated | 1.28 | 3.05 | 1.54 |
| | 20 virgin | <u>0.85</u> | <u>1.22</u> | <u>1.27</u> |
| | Difference | 0.43** | 1.83** | 0.27** |

** Significant at the 1% level.

Tables 12 and 13. The increase in soil strength in the tillage pan was found to be highly significant when compared to similar depths of virgin soil and also to that in soil above or below the tillage pan. Cultivation also resulted in higher soil strengths at soil depths above or below the pan than were found in the virgin soils.

The soil strengths in the Lakeland, Red Bay and Norfolk soils were evaluated using the six sites for each series. In each series, the soil strength of the tillage pans was significantly greater than at corresponding depths of the virgin soils. The two sites of the Orangeburg soil also showed a similar trend. From this data, it was evident that the pocket penetrometer was useful in providing data sufficiently accurate for evaluating the presence of a tillage pan. The depth of these tillage pans varied between locations and was usually not as thick in the Lakeland soils as in the other soil series.

In this study which included some pastures, the soil strength changes which were indicative of the pan were found at depths from 8 to 18 cm. The thickness of the tillage pan was between 10 to 18 cm in the Norfolk soils, 8 and 17 cm in the Red Bay soils, 12 and 13 cm in the Orangeburg soils, and 7 and 18 cm in the Lakeland soils.

In the field, it was observed that compaction in the tillage pans was usually the greatest about 2 cm above and below the zone of demarkation in organic matter content. This zone is the transition from the A_p horizon to the A_2 or B_1 horizon. The penetrometer readings taken in January and June showed close agreement where the sites were nearly coincident.

Bulk density

Bulk densities obtained for the core samples were examined statistically by the same method used for the soil strength data. Bulk densities of the tillage pan were highly significantly greater than those from the corresponding depths of the virgin soil as shown in Table 2. This increase was also highly significant in the pan compared to that above or below the pan. The bulk density of layers at depths above or below the pan in cultivated soils was significantly higher than corresponding depths of the virgin soil. The maximum bulk density was from the tillage pan in each soil series. Data for the different sites are reported in Appendix Table 13. The soil densities of the tillage pan of cultivated soil in the Lakeland, Red Bay, and Norfolk soils each were found to increase significantly when tillage pan compared to similar depths in the virgin soil of corresponding soil series. The packing of these soils was obviously associated with cultivation. This applied not only to soil in the pan, but to soil above or below the pan. In the Norfolk soils, the bulk density of the tillage pan was found to be in the range 1.52 to 1.72 g/cc. Similarly, these values for the Red Bay soils ranged from 1.50 to 1.66 while those for the two Orangeburg pans were from 1.59 to 1.71. Surprisingly, those for the Lakeland pans were also in a similar range which was from 1.55 to 1.70. The increase in bulk density with depth in the virgin soils was explained by the fact that the organic matter content decreased and the clay content increased.

Possibly other factors involved in this increase were decreasing aggregation, compaction from the increasing weight of soil with depth, and downward movement of colloids. These selected soils exhibited a higher density in the pan than below it. This was similar to that observed for the soil strength. According to the findings of Smith and

Table 2 -- Bulk density of soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|------------------|---------------|----------------------------------|-------------|-------------|
| | | Above | In | Below |
| ----- g/cc ----- | | | | |
| Norfolk | 6 cultivated | 1.49±0.07 | 1.63±0.09 | 1.57±0.06 |
| | 6 virgin | 1.32±0.19 | 1.46±0.08 | 1.56±0.05 |
| Red Bay | 6 cultivated | 1.40±0.17 | 1.59±0.07 | 1.50±0.10 |
| | 6 virgin | 1.34±0.14 | 1.46±0.08 | 1.48±0.07 |
| Orangeburg | 2 cultivated | 1.57±0.02 | 1.65±0.06 | 1.56±0.04 |
| | 2 virgin | 1.40±0.02 | 1.48±0.03 | 1.48±0.02 |
| Lakeland | 6 cultivated | 1.50±0.07 | 1.63±0.07 | 1.57±0.04 |
| | 6 virgin | 1.34±0.10 | 1.43±0.10 | 1.49±0.09 |
| Average | 20 cultivated | 1.47 | 1.62 | 1.55 |
| | 20 virgin | <u>1.35</u> | <u>1.46</u> | <u>1.51</u> |
| | Difference | 0.12** | 0.16** | 0.04** |

** Significant at the 1% level.

Robinson (99), the bulk densities of the tillage pans indicated a severe compaction.

Particle density

Some indication of the matrix in the soils in this study was revealed from the average particle density which was found. These data are given in Appendix Table 14. The particle densities increased slightly with the depth of the samples taken from either the cultivated or virgin sites. These values ranged from 2.57 to 2.75 g/cc. Since the particle density remains the same in the soil, uniformity was expected between cultivated and virgin paired sites. The variations between soil series and locations were also small for these densities. These data were used in the calculation of the total porosity.

Total porosity

Percentage of moist bulk volume not occupied by solids was calculated as porosity. Ratio of bulk density to particle density was obtained from values presented in the above sections. Porosity was expected to be less where compaction and movement of solids into the tillage pan resulted in decreases in pore spaces. The porosity measured the total pore space only.

Mean porosity and range of deviations from the mean are indicated in Table 3 for virgin and cultivated soil series. By the paired comparison technique, porosity of the tillage pan was significantly less than that at the corresponding depth of virgin soil. The tillage pan also contained significantly less pore space than soil above or below the pan. This latter effect was not found at corresponding depths in the virgin soils. These effects were in agreement with those found for the changes

Table 3 -- Pore space (total porosity) of soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|---------------|---------------|----------------------------------|----------------|----------------|
| | | Above | In | Below |
| ----- % ----- | | | | |
| Norfolk | 6 cultivated | 45.5 \pm 3.7 | 39.5 \pm 4.5 | 42.2 \pm 2.8 |
| | 6 virgin | 50.7 \pm 8.5 | 46.4 \pm 3.1 | 42.4 \pm 3.6 |
| Red Bay | 6 cultivated | 46.8 \pm 3.2 | 39.7 \pm 4.1 | 43.7 \pm 9.7 |
| | 6 virgin | 48.6 \pm 3.9 | 44.4 \pm 4.3 | 44.9 \pm 5.9 |
| Orangeburg | 2 cultivated | 41.3 \pm 1.6 | 38.9 \pm 2.2 | 43.0 \pm 1.2 |
| | 2 virgin | 46.8 \pm 1.9 | 44.9 \pm 1.2 | 45.5 \pm 0.3 |
| Lakeland | 6 cultivated | 44.3 \pm 2.3 | 39.7 \pm 3.5 | 42.0 \pm 1.3 |
| | 6 virgin | 49.8 \pm 3.7 | 46.8 \pm 4.3 | 44.8 \pm 3.7 |
| Average | 20 cultivated | 45.1 | 39.5 | 42.7 |
| | 20 virgin | <u>49.4</u> | <u>45.8</u> | <u>44.2</u> |
| | Difference | -4.3** | -6.3** | -1.5** |

** Significant at the 1% level.

in bulk density and soil strength that occurred in the tillage pans. Similarly, the cultivated soils were found to have lower values for pore space above and below the pan than were obtained at these depths in the corresponding virgin soil. This reduction was less than that for the tillage pan.

The average porosity of the tillage pans was 6.3% less than at the same depth of the virgin soil, 5.5% less than that in the soil above the pan, and 3.2% less than that below the pan. Detailed data for the different sites are given in Appendix Table 14. A rather surprising feature was the fact that the porosity of the pan was alike between the soil series; a difference of 0.8% was found between the average of the Orangeburg series and the Lakeland series which were the most different. From the greater porosity in the soil above the pan, soil organic matter was probably important since organic matter is known to be a favorable factor in soil structure. Conversely the lack of organic matter and the increased clay content at depths below the pan were factors likely to contribute to the decreased porosity at this depth. Further evidence of changes in the pore spaces is reported later in the discussions on thin sections and root penetration.

Location effects

The physical properties discussed earlier were evaluated by pooling the data such that the soil series were kept but the locations were considered as replications. To reveal the nature of the tillage pans in these selected soils, the data are arranged by counties in Table 4. Inspection of these data showed the tillage pans in Santa Rosa and Escambia Counties were higher in soil strength than those in Gadsden and Washington Counties. The soil series within each county also showed considerable

Table 4 -- Physical properties of tillage pans in the soils sampled from four counties

| Soil series | Profiles | Soil strength | Bulk density | Pore space |
|--------------------------|----------|--------------------|--------------|-------------|
| | | kg/cm ² | g/cc | % |
| <u>Gadsden County</u> | | | | |
| Norfolk | 3 | 2.50 | 1.68 | 37.7 |
| Red Bay | 3 | 3.30 | 1.63 | 37.9 |
| Lakeland | 2 | <u>2.75</u> | <u>1.65</u> | <u>37.6</u> |
| Average | | 2.85 | 1.65 | 37.7 |
| <u>Washington County</u> | | | | |
| Norfolk | 1 | 2.75 | 1.60 | 41.6 |
| Orangeburg | 2 | 3.10 | 1.65 | 38.9 |
| Lakeland | 2 | <u>2.10</u> | <u>1.60</u> | <u>41.6</u> |
| Average | | 2.65 | 1.62 | 40.7 |
| <u>Escambia County</u> | | | | |
| Norfolk | 1 | 3.50 | 1.52 | 44.0 |
| Red Bay | 2 | 3.90 | 1.56 | 42.1 |
| Lakeland | 2 | <u>3.50</u> | <u>1.63</u> | <u>39.6</u> |
| Average | | 3.63 | 1.57 | 41.4 |
| <u>Santa Rosa County</u> | | | | |
| Norfolk | 1 | 3.50 | 1.63 | 38.2 |
| Red Bay | 1 | <u>4.00</u> | <u>1.60</u> | <u>40.5</u> |
| Average | | 3.75 | 1.62 | 39.4 |

variation in soil strength. Bulk densities, however, showed a narrow range in the means for the counties and the soils within the county. The total porosities also were quite similar within the county and between counties. This uniformity was an important aspect of tillage pans since it showed the tillage pans from widely separated geographic locations were predictably alike in these physical properties. This meant that the processes of tillage pan formation were not localized by county or soil series within the scope of the soils selected for these studies. This uniformity also indicated that tillage pans were formed under a wide variety of textural and cultivation practices.

Particle size distribution

Soil texture varied considerably in the soils used for this study. Since particle size distribution is a stable feature of the soil, these data were useful in studying characteristics of the tillage pans. Previous work (22) showed that the particle size distribution was not modified appreciably by cultivation practices. Statistically, there was not a significant difference between particle size distribution of cultivated and virgin soils sampled at the same depths. Details of the sand, silt, and clay contents at the different sites are given in Appendix Table 15. The uniformity found between cultivated and virgin soil of the same series was good evidence that the concept of paired comparison within a single mapping unit was the correct approach for the study of the tillage pans. In general, sand content decreased and clay content increased with depth. The exception was at sites 5 and 20 where the sand was higher at the pan depth than above the pan. Variation in the silt and clay content was not attributed to pan formation. This meant that movement of silt and clay from the soil above the pan was not

measurable in the 20 cases studied. Thin sections taken above, in, and below the pan also confirmed there was not a massive flow into the large soil pores. Silt and clay contents of the Norfolk, Lakeland, and Red Bay soils from Escambia County were higher than in these soils from Gadsden and Washington Counties.

To test the effect of fineness of texture on tillage pan properties, five tillage pans were selected from each of three counties, regardless of soil series, but arranged in progressive order from the coarsest to the finest texture, Appendix Table 16. Analysis of variance of these data showed no significant effect for texture or between counties for bulk density or total porosity. The soil strength of these pans was not significantly different with change in texture but there was a significant difference between counties at the 5% level but not at the 1% level. This study supported the contention, expressed above, that tillage pans were formed by processes that did not involve necessarily silt or clay in any definite proportion at these selected locations.

Soil reaction

Past histories of the liming and fertilization of the cultivated soils were not available for the 20 soils in this study. In general, the pH of cultivated soil was higher than that of the corresponding virgin soil. These data, Appendix Table 17, did not indicate that the tillage pans were any more acid in character than soil below the pan or at the same depth in the virgin soil. Since soil reaction is a somewhat transient factor in terms of the years of cultivation practices, these values were indicative of conditions only at the time of sampling. Soil reaction of the cultivated Norfolk soils ranged from pH 5.1 to 6.7 compared to a range of pH 4.8 to 5.3 in the virgin soil. The cultivated

Red Bay soils were found to have a pH range from 4.6 to 6.1 compared to one from 5.1 to 5.8 in the virgin soil. The Orangeburg soils analyzed in the pH range from 4.1 to 5.5. The Lakeland samples from the cultivated area had a pH range of 4.7 to 6.7; those from the virgin sites were in the range pH 4.4 to 5.7.

Organic matter content

The core samples from the tillage pan were taken where the upper horizon merged with next horizon since this portion of the tillage pan generally exhibited the most soil strength. Examination of the paired comparisons for the Norfolk soil showed a significantly higher organic matter content in the tillage pans than at the corresponding depth of the virgin soil as shown in Table 5. Tillage pans occurring in Orangeburg soils were lower in organic matter than in the same depth of the virgin soil; the reverse was true for the Red Bay soils; and, tillage pans of Lakeland soils contained similar amounts of organic matter as corresponding depths in the virgin samples. At depths above and below the pan, there was a highly significant reduction in organic matter content in the cultivated soil compared to that at similar depth in the virgin soil.

Examination of the thin sections from these soils showed many of the large pores in the tillage pan were filled with organic matter. The organic matter probably was porous to water but acted as a filter for removal of ions or colloids descending into the profile. This probably helped precipitate the Al, Fe, and Si, that may have entered this portion of the soil from the soil above it. Since organic matter is known to be a factor in soil structure or peds (9, 15), cementing action by some of the organic matter, perhaps of recent microbial origin, probably resulted. Where cementation and filtration

Table 5 -- Organic matter content of soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|---------------|---------------|----------------------------------|-------------|-------------|
| | | Above | In | Below |
| ----- % ----- | | | | |
| Norfolk | 6 cultivated | 1.60±0.81 | 1.10±0.46* | 0.39±0.21 |
| | 6 virgin | 1.93±0.73 | 0.75±0.45 | 0.29±0.18 |
| Red Bay | 6 cultivated | 2.34±1.42 | 1.40±0.87 | 0.37±0.11 |
| | 6 virgin | 3.08±2.50 | 0.98±0.58 | 0.37±0.14 |
| Orangeburg | 2 cultivated | 1.31±0.33 | 1.21±0.43 | 0.42±0.08 |
| | 2 virgin | 2.78±0.22 | 1.45±0.13 | 0.93±0.01 |
| Lakeland | 6 cultivated | 1.21±0.52 | 0.60±0.22 | 0.18±0.10 |
| | 6 virgin | 1.28±0.29 | 0.60±0.21 | 0.29±0.14 |
| Average | 20 cultivated | 1.69 | 1.04 | 0.30 |
| | 20 virgin | <u>2.22</u> | <u>0.85</u> | <u>0.40</u> |
| | Difference | -0.53** | 0.19** | -0.10** |

* Difference between Norfolk pan and virgin soil at this depth is significant at the 5% level.

** Significant at the 1% level.

processes associated with the organic matter resulted in a bridge between sand or silt particles, some increase in the soil strength occurred. Compaction of the soil, by the weight of machinery or by hooves of animals compressed the matrix and the organic matter in the pores. Subsequently, tillage pans were formed when the matrix became rigid.

Organic matter content decreased with depth in all the soils studied, as shown in Table 5 and Appendix Table 17. Origin of this organic matter was principally leaf residue microbially altered to humus and is resistant to rapid decomposition in the soil. Under intensive cultivation with the use of lime and fertilizer, further microbial decomposition of the organic matter occurred. The organic matter in the cultivated soil was derived partially from crop residues. The organic matter content below the pans may have resulted from illuviation, roots, or animal activity. Organic content in the virgin soils at this depth was only slightly greater than that in the cultivated soils.

Peroxide extraction

Destruction of the soil organic matter with hydrogen peroxide and subsequent removal of soluble ions in dilute salt solution were essentially the extraction processes employed. The Al, Fe, and Si removed by this peroxide extraction were assumed to have been associated with the organic matter. To evaluate this relationship, the data, which are given in Appendix Table 18, were subjected to regression analysis with the organic matter content as the independent variable. Where organic matter content was very low, negligible Fe or Si was found in the peroxide extract. The soluble Fe increased as a significant linear function of the increase in organic matter content, as shown in Fig. 1. Similarly, the soluble Si content of the extract was proportional to the

soil organic matter level (Fig. 2). The soluble Al was appreciable where organic matter content was very low, which was to be expected from the extraction of the acid subsoils by a salt solution. However, soluble Al increased linearly with increase in the level of soil organic matter that was present in the soil (Fig. 3).

One possible explanation for these linear relationships, which were in common to both the virgin and cultivated soils, was that the Al, Fe, and Si were bonded to the organic matter. Another explanation was that the peroxide extraction generated sufficient acidity to dissolve some inorganic compounds. The data for the comparisons, shown in Table 6 and Appendix Table 18, were indicative that the peroxide extraction removed significantly less Al and Fe from the cultivated than from the virgin soil. A possible explanation of this decrease was that lime and phosphate additions had reduced the supply of Fe and Al, passing through the organic matter in the pan. The Si values were alike for the paired comparisons at the pan depth.

From the work of Franzmeier and Simonson (32) amorphous material in podzol B horizons was a complex mixture of Al, Fe, and organic matter. Previous investigations (27) with Coastal Plain clays showed a high amorphous content from the A₂ and B₁ horizons. Bonding of Al and Fe with the carboxylic groups of the soil organic matter was reported by Schnitzer and Skinner (93, 94). In the soils used in these studies, movement of soluble Si, Fe, and Al was probably involved over the span of years in the development of the tillage pan. In the pan, filtration by the organic matter may have promoted precipitation of Fe, Si, and Al from the soil solution.

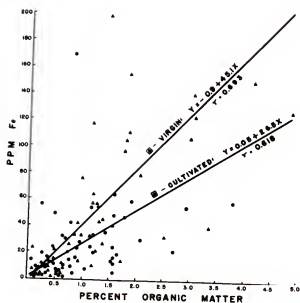


Fig. 1 -- Relationship between the Fe removed by peroxide extraction and the soil organic matter content of the virgin and cultivated soils.

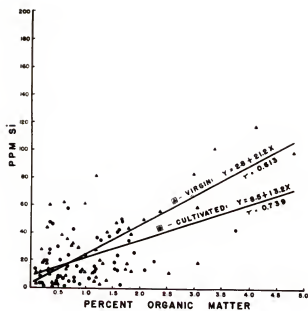


Fig. 2 -- Relationship between the Si removed by peroxide extraction and the soil organic matter content of the virgin and cultivated soils.

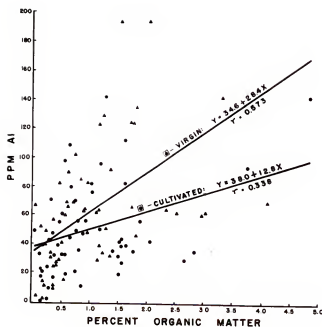


Fig. 3 -- Relationship between the Al removed by peroxide extraction and the soil organic matter content of the virgin and cultivated soils.

Table 6 -- Extractable Al, Fe, and Si removed sequentially by peroxide, citrate-dithionite, and hot 0.5N NaOH from soil samples of 20 tillage pans and the corresponding depths in virgin profiles

| Extractant | Element | Cultivated soil | Virgin soil | Differences |
|--------------------------|---------|--------------------|----------------|-------------|
| ----- ppm ----- | | | | |
| Peroxide | Al | 54.4 | 71.4 | -17.0** |
| | Fe | 19.2 | 33.7 | -14.5** |
| | Si | 20.1 | 21.0 | - .9 |
| ----- mg/g of soil ----- | | | | |
| Citrate- dithionite | Al | 1.22 | 1.09 | + .13 |
| | Fe | 4.40 | 3.69 | + .71** |
| | Si | .65 | .49 | + .16** |
| ----- mg/g of soil ----- | | | | |
| 0.5N NaOH | Al | 4.05 | 3.08 | + .98** |
| | Si | 1.51 | 1.16 | + .35** |

** Significant at the 1% level; negative sign indicates virgin soil values are higher and a positive sign that cultivated soil values are higher.

Citrate-dithionite extraction

Iron -- The Fe extracted by the citrate-dithionite method from the 20 paired sets of soils was assumed to come from free iron oxides. By the paired comparison method, Fe values from soil depths above or below the tillage pan were similar for the virgin and cultivated soil, as shown in Tables 6 and 10. However, for the 20 comparisons, Fe was highly significantly greater in the tillage pans than at the corresponding depths of the virgin soil. By soil series, this increase was highly significant for the Lakeland soils, and significant for the Norfolk soils. The Fe extracted at the depth of the tillage pans was greater than that in the soil above and less than that in the soil below, Appendix Table 19. This increase with depth was similar to that found for the clay content. The process of Fe illuviation probably was similar to that for clay illuviation except that some of the Fe was also expected to be soluble. Presence of free Fe compounds in the tillage pan was favorable for both the cementation process and the reduction in pore space by Fe compounds.

Aluminum -- Approximately 30% as much Al as Fe was removed from these soils in the citrate-dithionite extraction. Statistically, as shown in Table 6, the Al extracted from the cultivated soil at the depth of the tillage pan was of the same magnitude as that from a similar layer of the virgin soil. Examination of the data from samples taken above or below the pan depth showed that the Al increased with depth both in cultivated and in virgin soils. Within soil series, the Al values were quite variable between sites. Between soil series, there was no significant difference in the average Al extracted. Some cultivated soils were higher in Al extracted than that found for the virgin soils. The data are reported in Appendix Table 20.

Origin of Al extracted by this procedure was presumably from amorphous compounds and surface areas of the colloid. The process of Fe dissolution was favorable also for exposing the Al and dissolving it. The citrate kept the Al soluble by complexing it. It would appear that tillage pans did not accumulate Al. This did not rule out the possibility that this Al was involved in the cementation process which leads to the greater soil strength in the tillage pan.

Silicon -- Considerable difficulty was encountered in determining Si in the citrate-dithionite extracts. It was found that citrate must be destroyed prior to measurement of the silicomolybdate colored complex. This required the process of drying an aliquot of the extract in the Pt dish and then destruction of the citrate by ashing. This was a more satisfactory method than destruction of citrate by aqua regia since dehydrated silica required transfer before being put in solution. Since several Pt dishes could be used at the same time, the procedure was suited to the determination of Si in a large number of these extractions. Hot sodium hydroxide dissolved the Si completely.

As shown in Table 6, the cultivated soils at the depth of the pans contained more Si extractable by this procedure than did the corresponding virgin soil. It was assumed that the Si was associated in some way with the Fe compounds which were dissolved by the reagent. The Si extracted from soil samples taken above or below the pan depth did not show a pattern consistent for cultivation or soil series. In contrast to the Al determination, large increases in extractable Si with increasing depth of sampling were not observed. The data for the 20 sites are presented in Appendix Table 21.

Extraction with hot 0.5N NaOH

The use of hot 0.5N NaOH was intended to remove the remainder of the amorphous Si and Al compounds in the soil. Because of the high pH, Fe solubility was essentially negligible. As prior work has shown (48), quartz and layer silicates were not appreciably affected by the alkalinity if the time of contact was kept to the 2.5 minutes which were specified.

Aluminum -- Comparison of Al removed by this alkaline extraction was made between cultivated and virgin soil taken at the pan depth. As shown in Table 6, a highly significant Al accumulation was found in the tillage pans compared to that at same depths of the virgin soil. The Al extraction from soil above the pan depth was usually less than that found at the pan depth. At most sites, more Al was extracted from the virgin soil than the cultivated soil. The Al removed by this reagent from soil samples taken below the pan showed most of the sites to have much higher Al values than those found in or above the pan. A consistent difference between soil from cultivated and virgin areas was not found in these Al data which are given in Appendix Table 20.

One reason for the lack of uniformity between sites was attributable to the fact that gibbsite was dissolved by the reagent. This was shown by DTA patterns run before and after the treatment. The amount of gibbsite was assumed to be the same in both the virgin and cultivated pair. Evidence concerning this is reported in a later section.

Silicon -- At the pan depths, the amount of Si extracted was very significantly greater than in the corresponding layer of the virgin soil, as is shown in Table 6. This increase was similar in magnitude to that found for the Al removed. In Appendix Table 21, the data for each site are given. Most of the cultivated sites were found to have higher

extractable Si at depths both above and below the pan than in corresponding depths of the virgin soil. The reasons for the exceptions to this were not known although some soils undoubtedly were under a better lime-program than others. A higher soil pH as a result of liming was expected to give a higher mobility of Si in the soil. Possibly, the Si extracted reflected the accumulation of amorphous Si which was deposited by diagenesis in the soil.

Combined sequential extraction data

The sequential removal of Al, Fe, and Si from the 20 paired sites revealed several interesting soil properties which were discussed in the above sections. However, combination of these data also assisted in characterization of tillage pans. The amounts extracted by the peroxide extraction were only 1% of the total. The citrate-dithionite extraction accounted for nearly 33% of the Si and Al removed and nearly 100% of the Fe. Differences between soil series are shown in Table 7.

Ratios -- The molar ratios that were found for each extraction and the combined extractions are reported in Table 8. The Fe/Si ratios were nearly 1.0 for the combined data for the four soils series. This suggested the silicate was Fe compound except that the Fe/Si ratio was from 2.2 to 4.1 in the soil series when citrate-dithionite extraction was employed. The latter ratios suggested most of the Fe was not in the silicate form which is in agreement with the general concept of free iron oxides in soils. With peroxide reagent, the ratios, except for Lakeland samples, indicated that Si was more extractable than the Fe fraction. The Fe/Al ratios for both the peroxide and the combined data were less than 0.5 for all four soils. This meant that less Fe than Al was extracted. The low ratios might be indicative of the nature of both organic and amorphous forms in these tillage pans.

Table 7 -- Sequential removal of Al, Fe, and Si from the tillage pans by extraction with peroxide, citrate-dithionite, and hot 0.5N NaOH solutions

| Extractant | Element | Soil series | | | |
|--|---------|-------------|---------|------------|----------|
| | | Norfolk | Red Bay | Orangeburg | Lakeland |
| ----- % of total amount extracted* ----- | | | | | |
| Peroxide | Al | 1.5 | 0.6 | 0.7 | 1.3 |
| | Fe | 0.3 | 0.3 | 0.4 | 1.4 |
| | Si | 1.2 | 0.7 | 0.8 | 1.1 |
| Citrate-dithionite | Al | 31.3 | 18.0 | 14.0 | 28.6 |
| | Fe | 99.7 | 99.7 | 99.6 | 98.6 |
| | Si | 25.1 | 27.7 | 34.1 | 41.8 |
| 0.5 <u>N</u> NaOH | Al | 67.2 | 81.4 | 85.3 | 69.1 |
| | Si | 73.7 | 71.6 | 65.1 | 57.1 |

* Average values.

Table 8 -- Molar ratios of the sequentially extractable Al, Fe, and Si in the tillage pans

| Extractant | Ratio | Soil series* | | | |
|--------------------|-------|--------------|---------|------------|----------|
| | | Norfolk | Red Bay | Orangeburg | Lakeland |
| Peroxide | Fe/Si | 0.25 | 0.48 | 0.50 | 1.21 |
| | Al/Si | 3.08 | 1.88 | 2.04 | 5.30 |
| | Fe/Al | 0.08 | 0.26 | 0.25 | 0.23 |
| Citrate-dithionite | Fe/Si | 3.42 | 4.14 | 2.94 | 2.21 |
| | Al/Si | 3.01 | 1.70 | 1.02 | 1.79 |
| | Fe/Al | 1.13 | 2.44 | 2.88 | 1.24 |
| 0.5N NaOH | Al/Si | 2.20 | 2.97 | 3.23 | 3.14 |
| Combined data | Fe/Si | 0.87 | 1.16 | 1.00 | 1.00 |
| | Al/Si | 2.26 | 2.62 | 2.47 | 2.72 |
| | Fe/Al | 0.38 | 0.44 | 0.40 | 0.36 |

* Average values.

The Al/Si molar ratios were in the range 2.26 to 2.72 for the four soil series using the combined sequential removals of these elements. This was much in excess of that expected for an Al silicate. As mentioned before, gibbsite complicated this picture although gibbsite was not detected in many of the clays from these pans. The Al/Si ratios from the citrate-dithionite extraction averaged from 1.02 to 3.01 depending on the soil series. There was also a wide range for this ratio between soil series for the peroxide extraction. These ratios indicated the Al forms were not principally silicates. The Al and Si extractable from the tillage pans were not associated in a predictable manner. It was likely that many compounds were involved in the amorphous forms that were present.

Aluminum -- The total Al removed by the sequential extraction was averaged for each soil series with respect to the pan depth and corresponding depths of the virgin soil, Table 9. Additional data for each site are given in Appendix Table 20. The tillage pans contained nearly 25% more Al than corresponding depths of the virgin soil. This highly significant increase was not found in similar comparisons of soil above the pan or below the pan. The Red Bay and Lakeland tillage pans were significantly higher in Al than the corresponding virgin soils. The Al increased with depth in the four soils. Orangeburg and Red Bay soils were higher in extractable Al than Norfolk or Lakeland soils. The Al was probably a factor both in cementation and packing of the pores in the pan.

Iron -- The Fe removal in the sequence revealed that there was a highly significant Fe accumulation in the tillage pan where the data for 20 comparisons were used. In Table 10, the average values for the comparisons made for soil above the pan were not significantly different;

Table 9 -- Aluminum extracted sequentially from soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|-----------------------------|---------------|----------------------------------|------------------|------------------|
| | | Above | In | Below |
| ----- mg Al/g of soil ----- | | | | |
| Norfolk | 6 cultivated | 3.18 \pm 1.01 | 4.14 \pm 3.10 | 7.20 \pm 5.98 |
| | 6 virgin | 2.93 \pm 1.65 | 3.69 \pm 2.09 | 6.52 \pm 4.90 |
| Red Bay | 6 cultivated | 5.80 \pm 3.45 | 8.29 \pm 5.41* | 14.55 \pm 9.91 |
| | 6 virgin | 4.35 \pm 2.75 | 5.61 \pm 3.00 | 10.22 \pm 6.19 |
| Orangeburg | 2 cultivated | 3.88 \pm 2.22 | 7.66 \pm 2.61 | 15.77 \pm 8.25 |
| | 2 virgin | 4.99 \pm 2.28 | 8.80 \pm 3.24 | 23.50 \pm 6.92 |
| Lakeland | 6 cultivated | 1.78 \pm 0.83 | 2.22 \pm 1.33* | 2.57 \pm 1.66 |
| | 6 virgin | 2.05 \pm 1.65 | 1.59 \pm 0.85 | 2.77 \pm 1.64 |
| Average | 20 cultivated | 3.61 | 5.16 | 8.87 |
| | 20 virgin | <u>3.30</u> | <u>4.19</u> | <u>8.20</u> |
| | Difference | 0.31 | 0.97** | 0.67 |

* Difference between cultivated and virgin soils at this depth is significant at the 5% level for the Red Bay and Lakeland series.

** Significant at the 1% level.

neither were those for soil taken below the pan. Within soil series, the tillage pan showed significant Fe accumulation only in the Norfolk and Lakeland soils but not in the Red Bay and Orangeburg samples. Some accumulation factors in the pan were probably obscured in the two latter soils because Fe increased with depth to considerably different degrees at different sites. Iron accumulation might be associated with cementation and packing processes within the pan. Data for each site are given in Appendix Table 19.

Silicon -- The total Si extracted showed considerable variation within sites of the soil series as shown in Appendix Tables 11 and 21. Comparison of cultivated and virgin soils revealed there was more extractable Si from the cultivated soils at all three depths examined. The tillage pans of Red Bay and Lakeland soils, when examined within soils series, were significantly higher in Si than virgin soil at corresponding depths. The trends for Norfolk and Orangeburg were similar. The extractable Si increased with depth in the four soils. Cultivation practices, which include liming and fertilization, resulted in an increased level of the extractable Si in the soil. Since many forms of Si are known to be excellent cementing agents, the Si in, and entering into, the tillage pan probably was a prime reason for cementation and an important factor in trapping other ions or material passing through the pores.

Other cations extracted

The extraction with acid ammonium acetate was made so that Ca, Mg, and K could be evaluated as factors in the tillage pans as found at the time of sampling. These analyses, which are reported in detail in Appendix Table 22, showed that Ca increased at all three depths in most of the cultivated soils compared to corresponding depths of virgin soil.

Table 10 -- Iron extracted sequentially from soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|-----------------------------|---------------|----------------------------------|-------------------|------------------|
| | | Above | In | Below |
| ----- mg Fe/g of soil ----- | | | | |
| Norfolk | 6 cultivated | 1.91 \pm 0.81 | 3.27 \pm 1.77* | 6.83 \pm 5.02 |
| | 6 virgin | 2.00 \pm 0.72 | 2.56 \pm 0.95 | 7.43 \pm 5.54 |
| Red Bay | 6 cultivated | 4.50 \pm 2.80 | 7.58 \pm 4.55 | 10.50 \pm 5.70 |
| | 6 virgin | 4.39 \pm 2.74 | 6.13 \pm 4.37 | 10.15 \pm 4.56 |
| Orangeburg | 2 cultivated | 3.83 \pm 0.14 | 6.43 \pm 0.98 | 13.40 \pm 0.20 |
| | 2 virgin | 5.12 \pm 0.54 | 7.89 \pm 0.36 | 19.75 \pm 4.95 |
| Lakeland | 6 cultivated | 1.40 \pm 0.73 | 1.67 \pm 0.94** | 2.16 \pm 1.29 |
| | 6 virgin | 1.04 \pm 0.63 | 0.98 \pm 0.32 | 2.38 \pm 1.47 |
| Average | 20 cultivated | 2.72 | 4.40 | 7.18 |
| | 20 virgin | <u>2.74</u> | <u>3.69</u> | <u>7.96</u> |
| | Difference | -0.02 | 0.71** | -0.78 |

* Difference between Norfolk pan and virgin soil at the depth indicated is significant at the 5% level.

** Significant increase at the 1% level for 20 sites and in the Lakeland tillage pans over the virgin soil.

Table 11 -- Silicon extracted sequentially from soils used in the tillage pan study

| Soil series | Profiles | Position relative to tillage pan | | |
|-----------------------------|---------------|----------------------------------|-------------|-------------|
| | | Above | In | Below |
| ----- mg Si/g of soil ----- | | | | |
| Norfolk | 6 cultivated | 1.45±0.93 | 1.90±1.01 | 2.79±1.50 |
| | 6 virgin | 1.60±0.94 | 1.59±0.56 | 2.56±1.28 |
| Red Bay | 6 cultivated | 1.99±1.34 | 3.30±0.67 * | 4.26±1.10 |
| | 6 virgin | 1.53±0.34 | 2.46±1.19 | 3.04±0.91 |
| Orangeburg | 2 cultivated | 1.67±0.95 | 3.24±1.27 | 3.21±0.05 |
| | 2 virgin | 1.71±0.33 | 2.32±0.44 | 3.68±1.44 |
| Lakeland | 6 cultivated | 0.87±0.49 | 0.85±0.43 * | 1.50±1.04 |
| | 6 virgin | 0.84±0.60 | 0.68±0.45 | 1.30±0.89 |
| Average | 20 cultivated | 1.89 | 2.44 | 2.88 |
| | 20 virgin | <u>1.36</u> | <u>2.19</u> | <u>2.44</u> |
| | Difference | 0.53** | 0.25** | 0.44** |

* Silicon from Red Bay pans or Lakeland pans is significantly greater than in corresponding virgin soil.

** Significant at the 1% level.

This was to be expected since amounts of lime and fertilizer used would be a variable. The values for Mg and K also were higher in the cultivated soil at all three depths. The increased levels in the tillage pan were, in general, lower than in the soil above the pan and higher than those below the pan. These amounts were not of sufficient magnitude to be considered as a factor in pan formation. It was not determined whether silicates of these cations were insoluble in the acetate extractant. Therefore, the presence of the Ca, Mg, and K in the pans appeared to be as free exchangeable cations. The soil reaction indicated cation saturation was moderately high.

Differential thermal analysis

In this study, the endothermic patterns by DTA were unique in that the three depths of each profile were programmed at the one time. This made conditions for evaluating changes in the tillage pan as uniform as was instrumentally possible. This was also helped by having the clays all previously dessicated to the same degree by the low temperature drying. The endotherms were in the region from 50-150C, 280-330C, and 525-600C. The area under the peak was obtained with a planimeter. Each peak was expressed as the percentage of the total endothermic area. The resulting data for each site and soil series are given in Appendix Table 23.

With few exceptions, the endotherm area at the lowest temperature range was higher in clay from the cultivated soil than the virgin counterpart. The endotherms in the region near 300C were derived from gibbsite. The clays from the virgin sites were higher in gibbsite than those from the cultivated sites although the opposite was found at sites 1, 2, 7, 9, 10, 12, and 20. A major portion of the variation in gibbsite

between sites was attributable to the highest content being found in samples from Santa Rosa and Escambia Counties. The endotherms in the region from 525-600C resulted from dehydroxylation of 1:1 layer lattice silicates which were kaolinite and halloysite as interpreted from prior work with some soils from these counties (27). The areas under this endotherm were nearly the same magnitude between pairs of the cultivated and virgin soil; the principal exceptions were noted for sites 2, 7, 10, 17, and 19. From the DTA patterns, the soil series were somewhat alike in the distribution of the endotherm area. This suggested that the clays were somewhat similar in nature. The patterns also revealed that the cultivated soils were generally alike the virgin soils in the type of clay present. This is illustrated in Fig. 4 for a Norfolk soil, in Fig. 5 for a Red Bay soil, in Fig. 6 for an Orangeburg soil, and in Fig. 7 for a Lakeland soil. These patterns also show the consistent nature of the clay sampled at the three depths being studied.

Tillage pan patterns -- The DTA patterns found for the tillage pans averaged 20% of the endothermic area in the region from 50-150C with only a difference of 2% from this value for the means of the four soil series. The Norfolk and Lakeland patterns showed less area for the endotherm than that for clay above the pan but more than that below the pan. The Red Bay patterns showed more area than that found in clay from above the pan and less than that below the pan. The Orangeburg patterns also showed larger endotherms in the pan than above the pan but these were lower than those found below the pan. Since the drying of the clay removed most of the free water and destroyed the endothermic peak for hydrated halloysite, this endotherm was assumed to arise from amorphous compounds such as were reported by other workers (27, 69). The gibbsite content of the

tillage pans averaged 33% of the total endothermic area and the means for the soil series differed by only 3% from this value. Only the Orangeburg samples showed gibbsite to be lower in the pan than in the clay above the pan. The Norfolk and Lakeland pans were higher in gibbsite than in clay sampled below the pan and the reverse occurred for the Red Bay and Orangeburg pans. The 1:1 layer silicates accounted for an average of 47% of the endothermic area of these patterns. The means of the soil series were within 4% of this value. Only the Orangeburg was lower in this clay from the pan than that above the pan. However, only Red Bay clays were found to give greater endothermic peaks from these layer silicates than in clay below the pan. The evidence from the above data was that there was not a major difference between soil series or with depth in the nature of the clay in the tillage pans.

Patterns after the sequential extraction -- The sequential extraction was used to remove Fe, Al, and Si in amorphous forms or otherwise not within the lattice of the main crystalline components of soil clay. According to Jackson (48) the peroxide extraction removed free Mn oxides which might in some cases be hydrated. The citrate-dithionite extraction selectively dissolved limonite, hematite, goethite, and other amorphous iron oxides (46). Hot 0.5N NaOH was used by the method of Jackson (48) to remove amorphous forms of aluminosilicates, silica, and aluminum hydroxides. As pointed out by Dyal (25) and Jackson (48), gibbsite was also dissolved by this reagent. According to Jackson (48), poorly crystalline interlayers and halloysitic allophane were also dissolved by 0.5N NaOH in the 2.5 minutes extraction. However, crystalline quartz and layer silicates were not attacked appreciably according to the review given by Jackson (48).

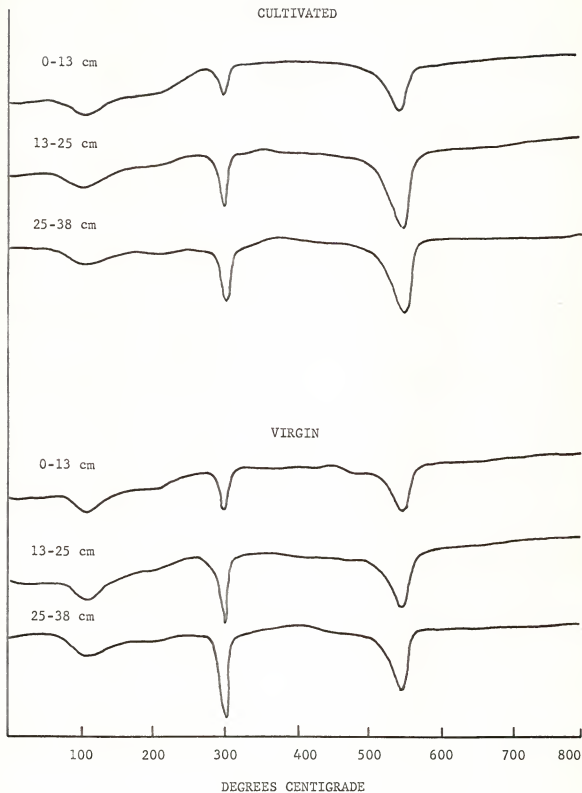


Fig. 4 -- DTA patterns of the clay fraction of cultivated and virgin Norfolk soils from Washington County at site 3.

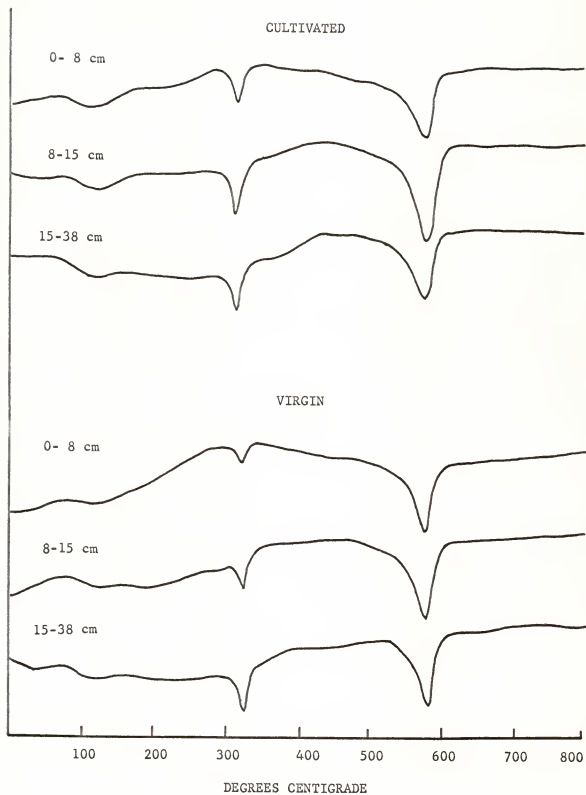


Fig. 5 -- DTA patterns of the clay fraction of cultivated and virgin Red Bay soils from Gadsden County at site 7.

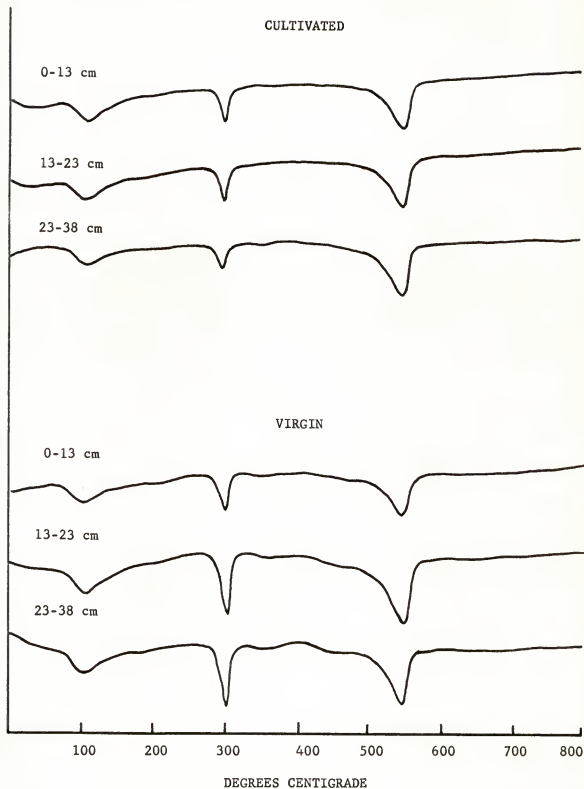


Fig. 6 -- DTA patterns of the clay fraction of cultivated and virgin Orangeburg soils from Washington County at site 13.

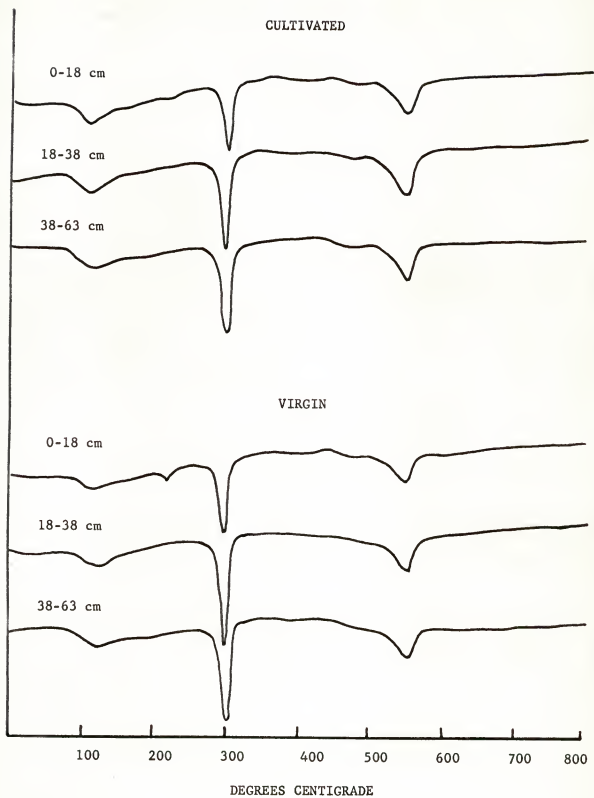


Fig. 7 -- DTA patterns of the clay fraction of cultivated and virgin Lakeland soils from Washington County at site 18.

The DTA patterns of the clays after the sequential extraction showed a complete loss of the endotherms in the region from 280-330C. This meant that the gibbsite was dissolved in the process. In Fig. 8, the Norfolk clay from site 3 is clearly devoid of gibbsite. However, the endotherms at the low temperature range persisted. This peak was probably from layer lattice minerals, possibly vermiculite, since the extractions removed the amorphous materials. The amount was magnified because crystalline clay was concentrated by the removal of amorphous and gibbsite components. This was shown by the greater endotherm areas in the range 525-600C than were found as is illustrated by comparison of Fig. 8 and Fig. 4. The DTA patterns are shown in Fig. 9 for Red Bay clays, in Fig. 10 for the Orangeburg clays, and in Fig. 11 for the Lakeland clays. The interpretation is the same as that for the Norfolk clays in Fig. 8. The nature of the clay is discussed further in the section dealing with X-ray diffraction patterns.

X-ray diffraction patterns

X-ray diffraction patterns were used for the characterization of the crystalline minerals in the clay fraction of many soils in the present study. Ten of these were from tillage pans and 50 from other samples. From previous research (46), the kaolinite was identified from the first order diffraction spacing at 7.2A and the second order spacing at 3.57A; quartz by the spacings at 3.35 and 4.62A; gibbsite by the spacings at 4.85 and 4.37A; feldspar, similarly, from the 3.18 to 3.24A spacings, and lower intensities at 4.21 and 6.46A; and, montmorillonite was sought from the 18A spacing given with Mg saturation and glycerol solvation. The monochromator (Philips) was used to reduce the intensity of Fe back-scattering, and this gave a high intensity in the region from 2 to 40.

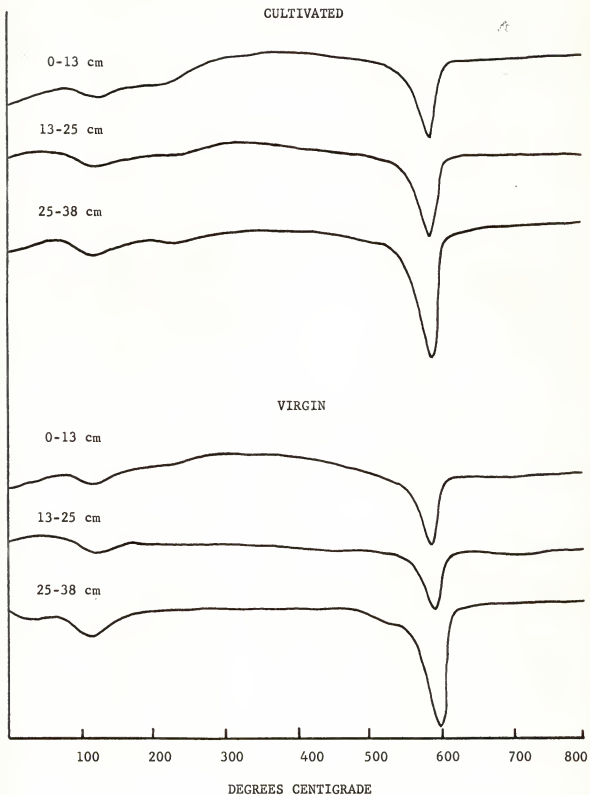


Fig. 8 -- DTA patterns of the clay fraction of cultivated and virgin Norfolk soils from site 3 after treatment with hot 0.5N NaOH for 2.5 minutes. Note the gibbsite shown in Fig. 4 by the endotherm at 300-330C has disappeared.

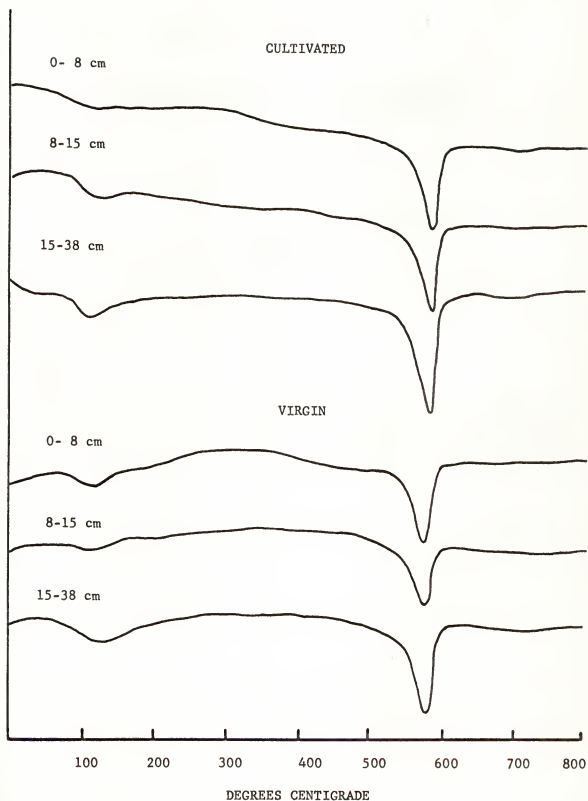


Fig. 9 -- DTA patterns of the clay fraction of cultivated and virgin Red Bay soils from site 7 after treatment with hot 0.5N NaOH for 2.5 minutes. Compare with Fig. 5.

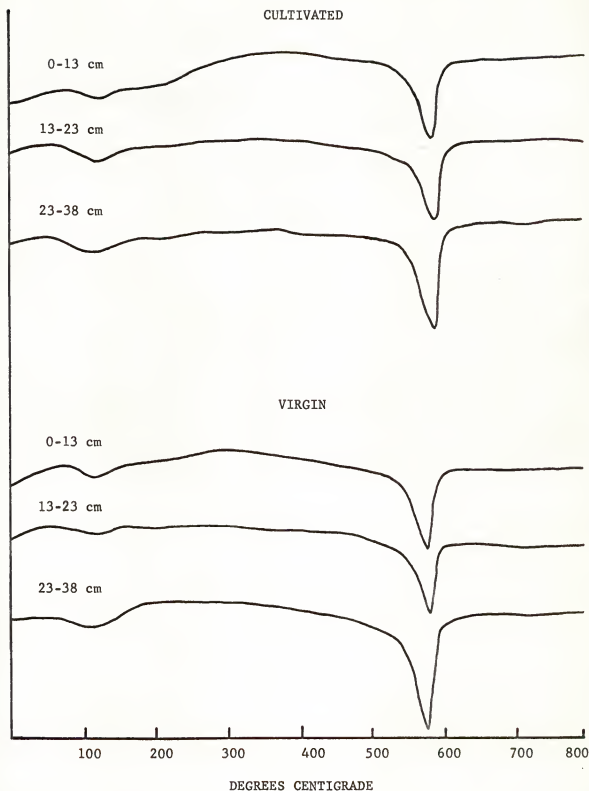


Fig. 10 -- DTA patterns of the clay fraction of cultivated and virgin Orangeburg soils from site 13 after treatment with hot 0.5N NaOH for 2.5 minutes. Compare with Fig. 6.

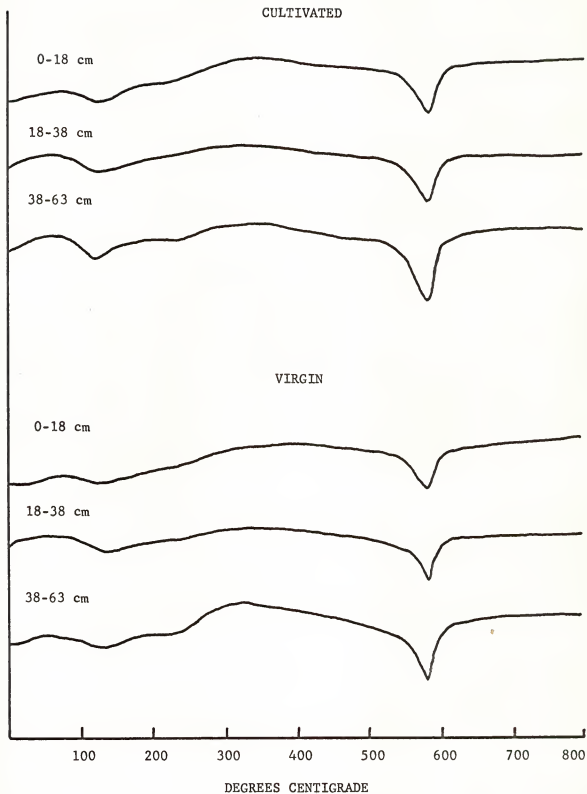


Fig. 11 -- DTA patterns of the clay fraction of cultivated and virgin Lakeland soils from site 18 after treatment with hot 0.5N NaOH for 2.5 minutes. Compare with Fig. 7.

In this case, the 18A reflection from montmorillonite was measured above this high but normal background intensity. The 14.2A spacing was assumed to be vermiculite. Presence of chlorite would reinforce the vermiculite and kaolinite reflections at the 14.4 and 7.2A spacings. The intersalation technique of Andrew, et al. (5) was not attempted to differentiate kaolinite from chlorite in these clays. Neither clay on the slides was heated to 500C, as proposed by Jackson (46), to test for the presence of chlorite since this treatment destroyed the kaolinite structure and collapsed vermiculite without changing the spacing of the chlorite.

The clay from the Norfolk soil at site 3 showed nearly similar X-ray diffraction patterns for cultivated and virgin samples. In Fig. 12, the dominant intensities at 7.2 and 3.56A are indicative of kaolinite, while the 14.2A spacing is probably vermiculite, and the 3.35A spacing is quartz. Since these clays were processed through the sequential extraction, the absence of gibbsite confirmed the findings by DTA. There appears to be a slight increase in the amount of kaolinite with depth. In Fig. 13, the corresponding clays from the virgin site showed similar patterns to those in Fig. 12, with possibly less intensity from the kaolinite reflections, particularly at the second depth.

A similar study of clays was made from Red Bay soil at site 7. The minerals present were similar to those found in the Norfolk soil described above which was taken about 100 miles distant. In Fig. 14, the clay from the cultivated portion of the site showed higher intensities at the 7.2 and 3.56A spacings than is shown for these spacings in the virgin soil in Fig. 15. A small amount of vermiculite and quartz is present in this soil. As in the case of the Norfolk clay, the crystallinity seems to be less in the clay from the virgin soil to a depth of 15 cm.

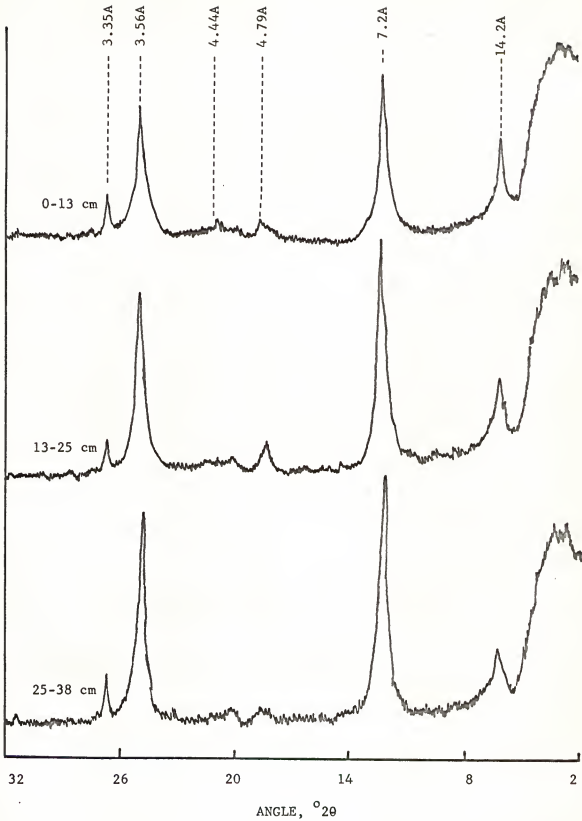


Fig. 12 -- X-ray diffraction patterns of the clay fraction of cultivated Norfolk soil at site 3.

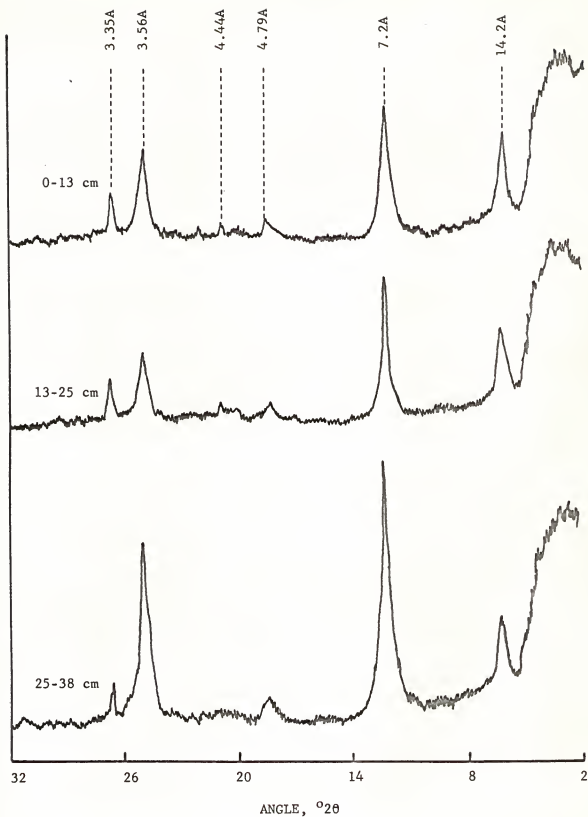


Fig. 13 -- X-ray diffraction patterns of the clay fraction of virgin Norfolk soil at site 3.

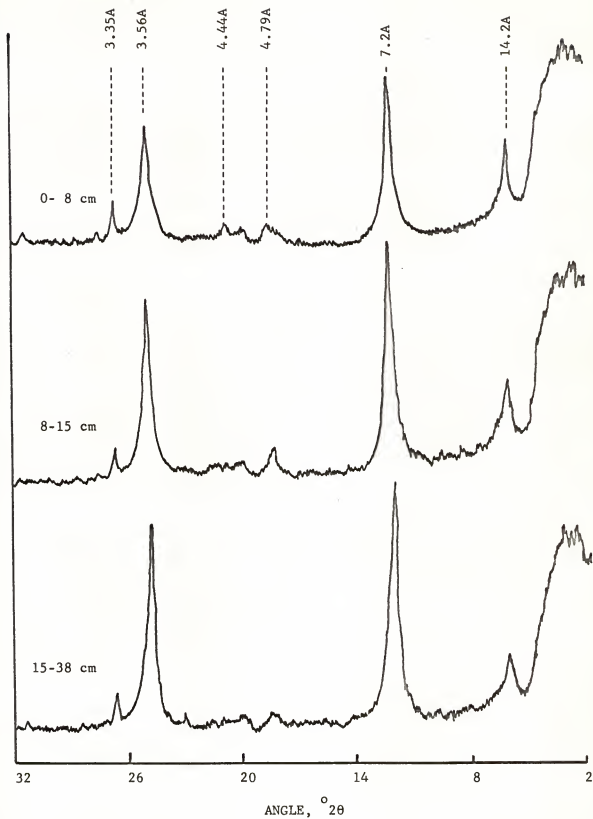


Fig. 14 -- X-ray diffraction patterns of the clay fraction of cultivated Red Bay soil at site 7.

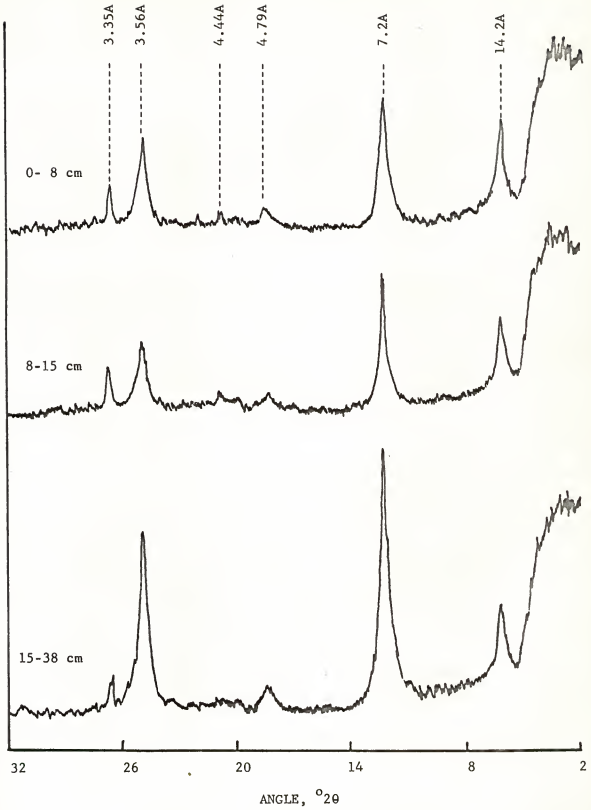


Fig. 15 -- X-ray diffraction patterns of the clay fraction of virgin Red Bay soil at site 7.

The X-ray diffraction patterns of the clay from the Orangeburg soil resembled those of Red Bay and Norfolk clays. In Fig. 16 (cultivated soil), the 7.2 and 3.56A peaks are much higher than those in Fig. 17 (virgin soil). Changes with depth are less pronounced than were found for the other two soil series.

The clay from the coarser textured Lakeland soil at site 18 in Washington County differed slightly from the other series in that more vermiculite, shown by the 14.2A spacing, was present. In Fig. 18, the clay from the tillage pan gave a similar diffraction pattern to that above or below the pan. The quartz line at 3.35A appears to be of the same magnitude of intensity as that for the virgin soil which is shown in Fig. 19. However, the intensities at 3.56 or 7.2A were higher in the cultivated soil at all depths, Fig. 18, than in the corresponding clays from the virgin soil as shown in Fig. 19. This was in agreement with similar evidence from the other three soil series. One reason for this may have been crystal growth of kaolinite or 1:1 layer lattice silicates under conditions existing in cultivated soils. Another possibility was that poorly crystalline minerals were weathered, and the soluble Al and Si illuviated from the cultivated soils. The latter effect was supported to some extent by an increase in the extractable Al and Si that was found in tillage pans. With time, this removal probably resulted in an apparent concentration or increase in crystallinity. Amorphous Al, Fe, and Si removal by selective dissolution was reported by Jackson (48) to increase the intensities of montmorillinite and vermiculite spacings. Natural removal was therefore likely to have a similar effect.

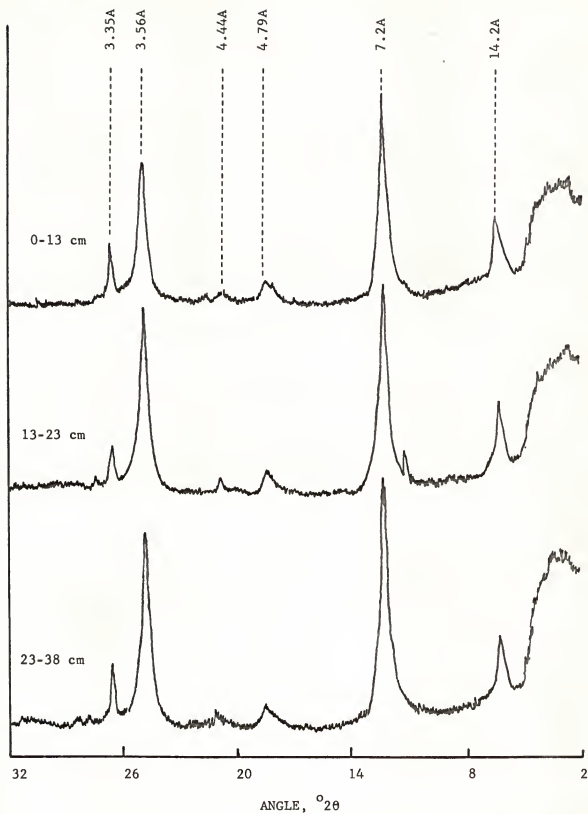


Fig. 16 -- X-ray diffraction patterns of the clay fraction of cultivated Orangeburg soil at site 13.

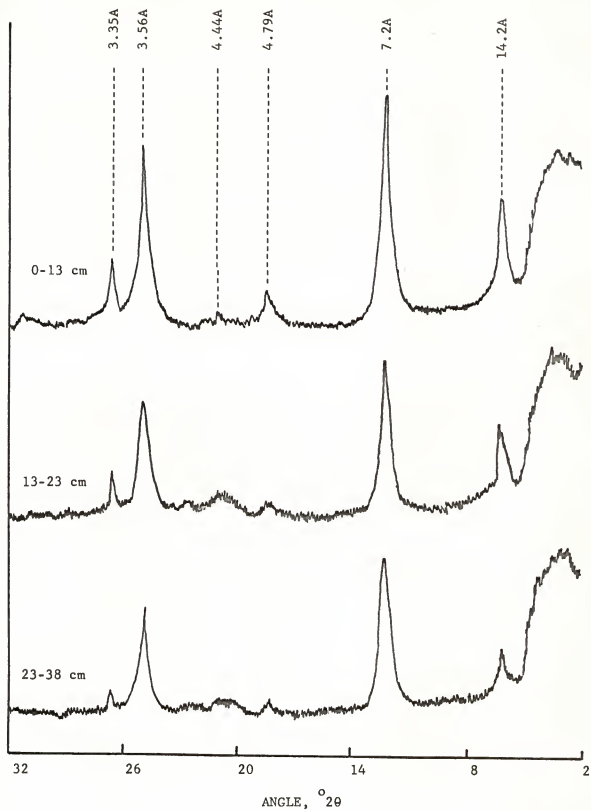


Fig. 17 -- X-ray diffraction patterns of the clay fraction of virgin Orangeburg soil at site 13.

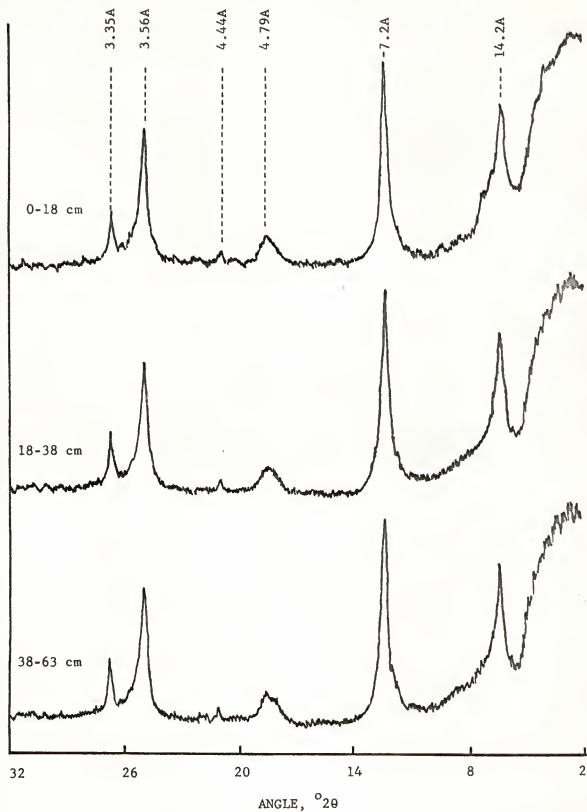


Fig. 18 -- X-ray diffraction patterns of the clay fraction of cultivated Lakeland soil at site 18.

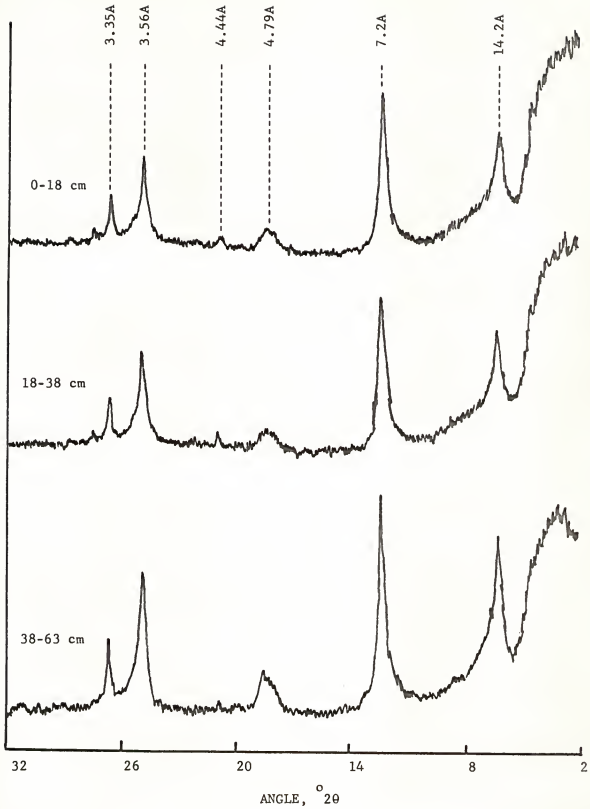


Fig. 19 -- X-ray diffraction patterns of the clay fraction of virgin Lakeland soil at site 18.

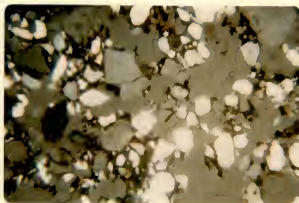
Thin section microscopy

Examination invariably showed that the fabric of the thin sections from the tillage pan was much more closely packed than in those sections taken above or below the pan. This was in agreement with the work of McCracken and Weed (68). At corresponding depths of the virgin soil, thin sections showed many rather large pores and infrequent contact of sand grains. In the tillage pans, the effect of compaction was evident since pore spaces were small and sand grains were in close contact. Very rarely was any evidence of oriented clay skins noted in these thin sections. This was not entirely unexpected since very little 2:1 layer lattice minerals were present, and amorphous clays do not exhibit birefringence upon illuviation. Some of the pores appeared to be filled with organic matter in many of the thin sections.

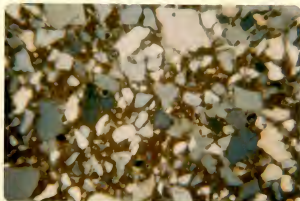
In Fig. 20, photomicrographs shown are of thin sections representing the three depths of Red Bay soil from a cultivated area at site 7 which is in Gadsden County. The larger angular areas of different colors are sand and silt quartz grains. The dark brown and brown areas are organic matter and clay. The uniformly colored, irregular shaped, moderately dark areas, in the remaining photomicrographs are pore spaces. Compaction in the tillage pan can be seen by the close clusters of sand grains and the lack of obvious pore spaces or voids. Above or below the pan the fabric has more space between sand grains, and more pore spaces are present. Obviously, the packing in the pan must be a physical obstacle to root penetration and expansion. In Fig. 21, the photomicrographs of thin sections from the corresponding virgin soil show a more open structure of the fabric than in the cultivated soil. Obviously, tillage can be seen to have some effect on the arrangement and packing

Depth
cm

0 - 8



8 - 16



16 - 32

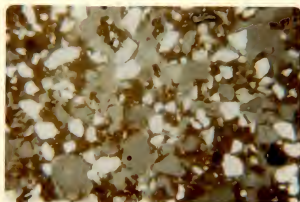
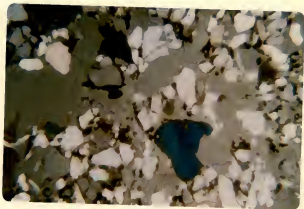


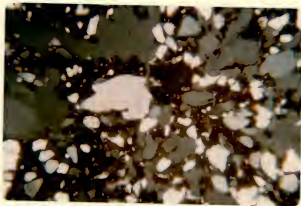
Fig. 20 -- Thin section microphotographs of cultivated Red Bay soil from site 7 (Gadsden County); taken with crossed polarized light, 25X.

Depth
cm

0 - 8



8 - 16



16 - 32

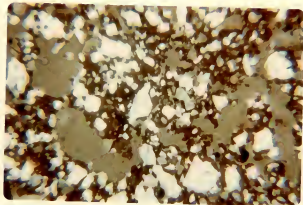


Fig. 21 -- Thin section microphotographs from the virgin Red Bay soil from site 7 (Gadsden County); taken with crossed polarized light, 25X.

of the soil particles when one compares virgin and cultivated sites above, in, or below the pan depth. This effect combined with cementation is in agreement with the property, reported above, that tillage pans possess both greater soil strength and a decreased porosity.

Examination of the thin sections from nine other tillage pans showed similar features to those discussed in connection with Fig. 20 and Fig. 21. This was true for the Red Bay, Norfolk, Orangeburg, and Lakeland comparisons. The tillage pans were not materially different with respect to the site or county from which they came. Differences in the coarse-textured Lakeland from Washington County and the more silty ones from Escambia County existed because the spaces between grains were occupied by smaller particles in the latter case.

There was little doubt, from these microscopic studies, that physical forces were involved in the formation of tillage pans since the spacings within the fabric were altered. However, there was no evidence of clay or silt changes that would suggest that clay skins or channel effects were factors in the pan formation.

The lack of corresponding compaction in the virgin soil showed that the pan formation was not a morphological feature unless cultivation had occurred. Number of years under cultivation was probably a factor in pan formation. Some of the soils had been under cultivation for a long time and evidenced by the aerial photographs which had been made about 20 years previously. The main feature not found in these thin sections of cultivated soil was the larger interrelated pores which were seen in the thin sections from the virgin soil. Possibly, cultivation practices maintained adequate porosity in the soil above that zone which became the tillage pan. In the pan zone, over a period of time, settling of the

coarser grains in the fabric occurred and compaction was likely to increase. This resulted, logically, in small pore spaces. As the process proceeded, these pores were partially filled with the Al, Fe, and Si compounds, which were amorphous in nature. The soil then became structurally rigid as cementation processes proceeded between the components of the fabric. Evidence found by examination of these thin sections did not dispute such a hypothesis for the formation of tillage pans.

Tillage Pan Effects on Root Growth

Field investigations

Root systems of field crops were examined for possible effects of tillage pans on their growth characteristics. Soil scientists noted that the shallow rooting habits of crops in the Southeast played an important role in the inefficient use of water (8). In this investigation, the roots were examined in June at many of the sites previously visited the preceding January. After the pits were dug, depth and thickness of the tillage pan were determined by the pocket penetrometer. The roots above, in, and below the pan were exposed, examined, and sampled. Field corn was studied at ten locations; three were in Bermudagrass, three in Pensacola bahiagrass, and one in soybeans.

At all sites, where roots were found in the tillage pan, poor secondary root development was found compared to the root system above the pan or below the pan. An example of the difference in root growth in the tillage pan is shown in Fig. 22. Those roots that were in the pan were noted to be in cracks or old root channels in many instances. These roots were brittle in character and developed stubby secondary roots. At

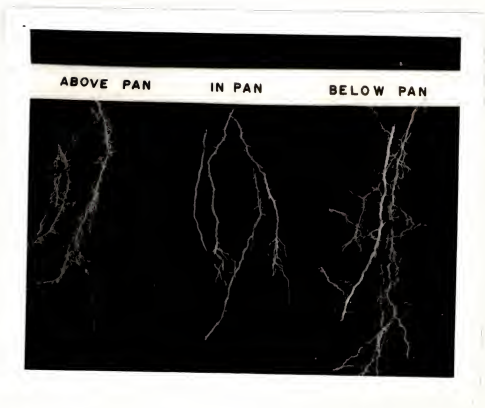


Fig. 22 -- Bermudagrass roots in the tillage pan of Lakeland sand show poor lateral development compared to the same root systems above or below the pan.

six sites out of 10, the corn roots either failed to penetrate the pan or were restricted to the upper portion of the pan. Grass roots were able to penetrate the tillage pan at the six sites examined. In the Orangeburg soil, neither the tap roots or lateral roots of cotton plants were able to penetrate the pan. Soybean roots were not found below the tillage pan at the site which was examined. However, in a later study made in September, soybean roots at the West Florida Experiment Station were found below the pan in a few instances.

Morphological examinations

Microscopic study of the cross sections of roots was made to determine if the roots that grew in the tillage pan were morphologically alike those above or below the pan. The tissue morphology of Bermudagrass, bahiagrass, and corn roots that grew in soil above the pan was considered to be normal. The cross sections of roots sampled below the pan were slightly irregular in shape compared to those above the pan. However, all roots from the tillage pan exhibited various degrees of deformation. These may be seen in Fig. 24, compared to Fig. 23. The epidermis was very irregular in shape and, in some cases, appeared to be ruptured. This shape suggested that the roots were confined to sharply angular channels, and the epidermis was either weakened or ruptured, whereas roots above or below the pan remained intact in the preparation processes. A possible explanation was that the roots in the pan were cemented to the soil fabric in some manner and were damaged when they were separated from the soil. Moreover, the stele and endodermis of such roots were not spherical in shape which indicated distortion by soil pressure.

In some of the corn and bahiagrass roots from the pan the cortical cells appeared to contain abnormal solids. This is shown in Fig. 25, and

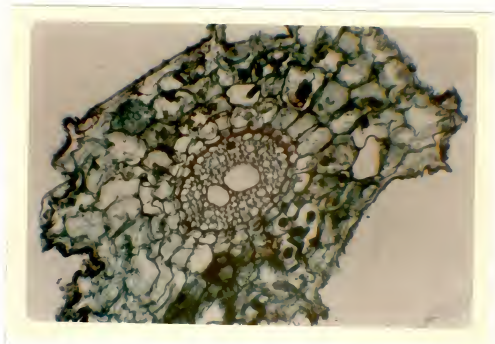


Fig. 23 -- Cross-section of distorted corn root found in a tillage pan, 100X.

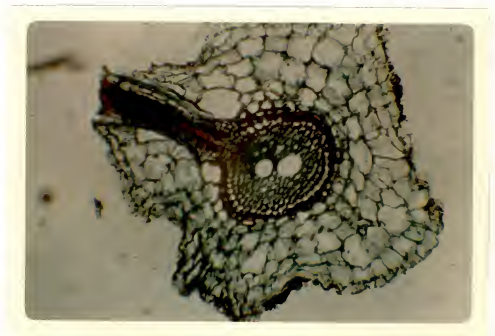


Fig. 24 -- Cross-section of distorted Bermudagrass root found in a tillage pan, 100X.

at high magnification in Fig. 26. These solids are granular in shape and are located mostly outside the stele. Such solids might be indicative of excess entry of such ions as Fe, Al, and Si into the roots and subsequent deposition. Such concentrations might be inhibiting root growth in the tillage pans.

Deformation was extreme in the corn roots from the tillage pan at six of eight sites which were studied. Roots of Bermudagrass were similarly deformed in two of the three sites investigated in comparison to those above the pan. The bahiagrass roots from three different tillage pans were quite morphologically different at two sites from roots taken above or below the pan.

Chemical studies

Alkaline extraction -- A measure of the Al and Si associated with the roots, after thorough washing, was obtained by the short treatment with hot 0.5N NaOH. These data are shown in Appendix Table 24. Assuming that this treatment dissolved chiefly amorphous compounds, the data showed higher values for both Al and Si where the roots were either taken in the pan or below it than that obtained for roots above the pan. There was a wide range in values between sites and a somewhat similar range of values for the soil series. These values were small in comparison to the total content of the root samples, Appendix Table 25. It was logical to assume that the roots themselves contained appreciable amounts of Al and Si. The Fe content was not extractable by the alkaline treatment.

Root ash -- The Al content of the corn roots ranged from 429 to 2,820 ppm on the fresh weight basis. The average was 1,150 ppm for roots above the pan, compared to 1,530 ppm in the pan, and 1,850 ppm below the pan for fewer samples. From these ten sites, all four soils appeared

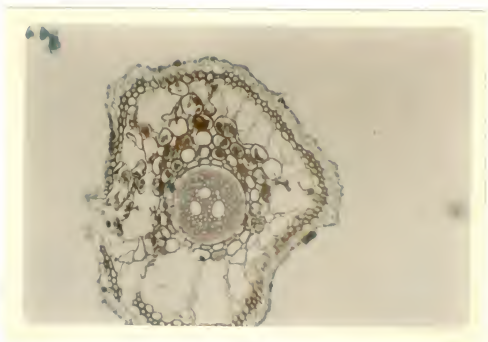


Fig. 25 -- Cross-section of distorted bahiagrass root found in a tillage pan, 100X.

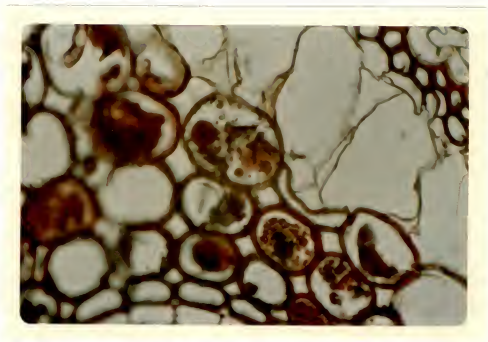


Fig. 26 -- Enlarged cross-section of a portion of the bahiagrass roots shown in Fig. 25, 450X. Note the inclusions within the cells.

to supply nearly the same Al to the roots. Grass roots and soybean roots appeared to have as high or higher Al content than corn at each depth sampled, Appendix Table 25.

The Fe content of the corn roots ranged from 139 to 1,900 ppm. Roots sampled above the tillage pan were usually lower in Fe than those from the pan, or below it. The Fe on the roots also appeared to increase with depth of the roots in the soil. The grass roots and soybean roots were within the Fe range of values found for the corn roots. Roots from the four soil series were somewhat alike in the amount of Fe found, Appendix Table 25.

The Si content was very much higher than that found by the extraction with 0.5N NaOH. Corn roots taken above the pan contained an average of 1,180 ppm of Si, compared to a value of 1,420 ppm in roots from the pan, and 1,700 ppm below the pan. The grass roots were higher in Si than the corn, as may be observed in Appendix Table 25. It was somewhat surprising to find that roots from the Lakeland soil sites were as high in Si as those from the other three soil series.

From the Al, Si, and Fe data, roots in the pan did not appear to be suffering from toxicity, since higher values were found in the roots taken below the pan where growth appeared to be better. The amounts of Si present paralleled the amounts of Al found which suggested some form of Al silicate might be present. Possibly, Fe also was present as a silicate. Such compounds would be expected to be insoluble in the cells.

The Ca content of the root ash showed a very wide range, from 350 to 1,500 ppm on the fresh root basis. Roots taken below the pan showed a Ca content in the range from 40 to 1,500 ppm, and those in the pan contained from 36 to 955 ppm. Possibly, the lower Ca values might be indicative of Ca deficiency. However, these low values also were found

in the roots taken above the pan. In 11 cases out of 18, the Ca found in the roots from the pan was higher than that in corresponding roots found above the pan. Details from the different sites are given in Appendix Table 26.

The Mg content was found to be in the range 30 to 319 ppm in those roots. At 15 out of 17 sites, Mg was higher in roots from the pan than those above the pan. The lowest Mg values were possibly indicative of Mg insufficiency, but these were not confined to the location of the roots or the soil series.

The K content of the roots ranged from 74 to 1,660 ppm of the fresh weight. In nine cases out of 17, the roots from the tillage pan were higher in K than those sampled above the pan. The wide variability was probably associated with the fertility of the soil; as previously indicated, the samples were taken without prior knowledge of the fertilization. It did not appear that root deformation in the pan necessarily resulted in a lower K content in the roots.

Soil analyses -- Soil samples were taken where the roots were growing. The soil analyses are reported in Appendix Table 27. The pH of soil from the 17 tillage pans examined for the root study was very nearly the same as in the soil above the pan or below the pan. The unfavorable root growth in the tillage pans occurred in the pH range from 4.9 to 6.7. This indicated that soil acidity was not a serious limiting feature to root growth in the tillage pan.

The Ca values in most of the soils above the pan were higher than those in the pan. This was expected, since the liming and fertilization were made at this depth. The Ca values in the tillage pan ranged from 46 to 465 ppm. Within this range, the two Orangeburg samples averaged 82 ppm of Ca, whereas the average value for Norfolk, Red Bay, and Lakeland samples from the tillage pan was 153, 170, and 172 ppm, respectively.

The soil Ca values did not show good agreement with the root Ca values in the ranges studied. Possibly the restricted nature of the root system in the pan contributed to this lack of agreement. However, the roots above and below the pan also were not found to have Ca values that reflected the soil Ca level that was present. The complications of sites, crops, soils, and depth of roots were contributing factors that could not be fully assessed in this limited study of Ca in soil root relationships.

The Mg values in the soil samples ranged from 3 to 185 ppm. At three sites of Norfolk, one of Red Bay, two of Orangeburg, and three of Lakeland, the Mg values were less than 15 ppm. However, roots from these soils were found to contain from 35 to 316 ppm of Mg, depending on the soil series and the site. These values for both soil and root Mg were not associated with the tillage pan since similar ranges were noted in samples taken above or below the pan. Details are shown in Appendix Table 27.

The K values in the soil samples ranged from a low of 10 ppm to a high of 298 ppm. In most of the soils, the K found in the soil from the tillage pan was lower than that in the soil above the pan. The soil K and root K varied from site to site. There did not appear to be a predictable relationship between the soil K that was found and the root K. Apparently, the K supplying power of these soils and the fertilizer K were sufficient in the tillage pans for roots. Details are shown in Appendix Table 27.

The P status of the soils used in this study was low, particularly in soil from or below the tillage pan, Appendix Table 27. These lower values which ranged from 2 to 4 ppm of acetate-extractable P were found in all four soil series. Since roots below the pan grew well at similar

P values, it would appear that P nutrition was not necessarily a factor that limited root development in the tillage pans.

Combined effects

Adverse penetration of roots into the tillage pan and root deformities in the pan were primarily the results of a combination of physical factors. From the morphology of the roots in the pan, the obvious deformation suggested that expansion of the roots encountered irregular and rigid fabric surrounding the pore space that contained the root. This evidence was supported by the increased soil strength where changes in root penetration and development were observed. From the thin sections of the soil, a few, small pores were seen in the tillage pan, compared to large pores where roots grew well. Space for root development was a serious restriction in the tillage pan. Coupling of space and soil strength factors made it improbable that root development in the pan would be normal. From the crops and sites studied, root growth characterized the presence of tillage pans and was in excellent agreement with soil strength measurements of the upper boundary of the pan.

Another combined effect was soil fertility factors in the tillage pan and root nutrition in this soil. From past studies of virgin soils in Florida, Gammon, et al. (35) reported that most soils were natively low in fertility, organic matter decreased rapidly below the first horizon, and clay content increased with depth. These virgin conditions were modified by cultivation and management practices. Cumulative compaction occurred below the depth of tillage; the loose, incoherent structure of the virgin soil was subject to the pressures imposed because spaces between the sand particles contained very little material that could act resiliently. Fertilization of the Ap horizon resulted in salt

movement into the deeper horizons. Penetration of roots into the tillage pan may have followed some channels where those salts were moving with descending water. Other roots may have developed by random penetration of the tillage pans. The soil fertility in these pans resulted both from residues of past fertilization and from more recent intrusion of soluble salts. Soil and root analyses were not indicative of a characteristic deficiency of fertility in the tillage pans. However, the high amounts of Al, Si, and Fe associated with, and apparently within, the roots must have soil origin. The ionic absorption process could occur only if the soil solution were high in these ions which infers that much soluble Fe, Al, and Si were present around the roots. This was not a property that was confined to those roots from the tillage pans. Another possibility, which might be remote, was that solids were incorporated into the roots by pinocytosis. If this were the case, the microscopic examination of the young root tips would be expected to show inclusions in the epidermis, whereas they were noted near the endodermis. It did not appear that soil fertility was the main factor limiting growth of roots in the tillage pans.

A very important finding was that root growth was impeded by the tillage pan at widely separated sites of the four Coastal Plain soils. This was not limited to a crop or location. The properties affecting the root growth in the tillage pan appeared to be common to the rather large area which was studied. This meant that the tillage pans were prevalent and that the root systems were restricted by them.

Corrective practices

Better root systems from destruction of the tillage pan were recognized by Bartholomew and Fitts (8) as a major way for improvement of the

productivity of Coastal Plain soils. Subsoiling to fracture the pan was not as effective as subsoiling and deep fertilization or liming for increasing corn yields in these soils (8, 36, 80, 85). Robertson, et al. (85) have found that, in Florida, corn survived droughts of short duration better where subsoiling and deeply placed fertilizer had been practiced. They also noted that under severe drought conditions, the advantage of deeper root systems and a larger plant was lost. Their work also showed that residual benefits of subsoiling were small after the first crop.

One inherent feature that reduced the effectiveness of subsoiling and deep fertilization was the fact that the tillage pan was fractured, but the associated soil retained most of the physical properties present in the pan. The reason for this was that only where the chisel passed through the soil was there a complete destruction of the pan. This soil was therefore likely to continue to restrict root systems. A more logical system was deep plowing to turn the tillage pan and then pulverize the clods by discing or rotivation. This latter system was favorable for increasing both the depth of soil amended by lime and fertilizer residues, as well as the porosity for root penetration. Deep plowing has become a common practice in many of the Coastal Plain soils in Florida where soybeans and corn are grown. This practice was efficient in the destruction of most of the tillage pan, but tillage was not deep enough to remove all of it. Depth of plowing has not received serious research or attention, judging from the paucity of published papers on this subject for Coastal Plains soils.

CONCLUSION

Tillage pan characteristics in Lakeland, Norfolk, Red Bay, and Orangeburg soil series were investigated at 20 paired locations of cultivated and adjacent virgin areas. From field and laboratory studies, the following conclusions were made:

1. Presence of tillage pans was associated with greater soil strength, higher bulk density, and less pore space than above or below the pan or at corresponding depths in virgin soils.
2. Particle size distribution was statistically alike between cultivated and virgin soils at all sampling depths. This suggested clay illuviation was not a major factor in pan formation.
3. Tillage pans were significantly higher in organic matter than adjacent virgin soil horizons of the same depth.
4. Cementing agents probably accounted for the increased soil strength. Statistically, significant accumulations of Al, Fe, and Si were found in tillage pans by sequential extractions with hydrogen peroxide, citrate-dithionite, and hot 0.5N NaOH reagents.
5. The organic matter removal by peroxide resulted in Si, Al, and Fe solubilities that were proportional to the organic matter content.

6. Clay minerals were similar within each profile, at corresponding depths between paired locations, and in the tillage pans of the four soil series investigated. The hot 0.5N NaOH dissolved gibbsite in addition to amorphous Al compounds. This was confirmed by DTA and X-ray analysis.
7. The pH and acetate extractable Ca, Mg, K, and P increased in cultivated soils as compared to their virgin counterparts. Evidently, eluviated ions from overlying soil horizons increased the fertility of tillage pans.
8. Roots of field crops either failed to penetrate the tillage pans or were distorted in the pan. Lateral root growth was seriously restricted in the pan compared to the root development observed above or below the pan.
9. Chemical analyses of soil and roots failed to indicate a nutrient deficiency in the tillage pans, however, the roots were high in Si, Al, and Fe. In addition, some deposition of solids in the cortical tissue was noted.
10. From thin section studies, the tillage pans showed a compressed fabric lacking in large pore space compared to that found above or below the pan, or in the virgin soil. This evidence, coupled with the significant change in soil strength, indicated development of an unfavorable physical medium for root penetration and growth. This was probably a result of pore size being too small or too rigid for normal root development in the tillage pans.

SUMMARY

Tillage pans were characterized in Lakeland, Norfolk, Red Bay, and Orangeburg soils by comparison of cultivated and adjacent virgin soil in the same mapping units and with soil above or below the pan. Field studies were made at 20 sites located in four counties in Florida. Times of sampling were January and June, when the soil was nearly at field capacity. Site for each pit was selected so that cultivated and virgin soils were no further than 60 m apart. Location of the pit was decided from the uniformity of measurements made with a modified Proctor penetrometer. In the pit, soil strength was measured horizontally by the pocket penetrometer to delineate tillage pan depth and thickness. From this information, samples were taken of soil or roots above, in, and below the pan and soil at corresponding depths in the virgin soil. At each of these depths, a double cylinder, hammer-driven core sampler was used to obtain a known volume of soil for physical and chemical analyses. Seventeen of the cultivated sites were used for study of root growth and root analysis; several field crops were involved.

Physical measurements were used to characterize the tillage pans. In the four soil series, soil strength in the pan was more than twice that of the virgin soil; soil above the pan was nearly 50% higher in strength, and soil below the pan from 5 to 50% higher than that of the corresponding virgin soil. Soils strength above, in, and below the pan averaged 1.28, 3.05, and 1.54 kg/cm², respectively. Bulk densities increased from an average of 1.46 g/cc in the virgin soil to 1.62 in the

tillage pan; soil above the pan increased from 1.35 to 1.47 g/cc and below the pan from 1.51 to 1.55 g/cc, similarly. Total pore space decreased from 45.8% in the virgin soil to 39.5% in the tillage pans; there were also decreases in the porosity of the soil above and below the pan. Magnitude of these physical effects was alike between soil series, and variation within counties was alike that between counties.

Particle size distribution was statistically alike between the cultivated and virgin soil at each site. Evidence was not found that clay or silt content increased in the tillage pan. In the Norfolk and Red Bay tillage pans, average organic matter content was higher than that in the corresponding virgin soil. The reverse was true for Orangeburg soil. But, there was not a difference in organic matter content of cultivated and virgin Lakeland soil.

Cementing features to account for the increased soil strength were sought by sequential extraction with peroxide, citrate-dithionite and hot 0.5N NaOH reagents. Significant linear regressions were found which showed that with increasing organic matter content the Al, Fe, and Si extracted in the peroxide treatment also increased. Iron extracted by citrate-dithionite was significantly higher in Norfolk, Red Bay, and Lakeland pans than at similar depths of the virgin soils. This reagent also extracted Si and Al; the Fe/Si ratios ranged from 2.2 to 4.1 by soil series; the Al/Si ratios ranged from 1.0 to 3.0; and the Fe/Al ratios were from 1.1 to 2.9. The increase in Al values with depth was alike between cultivated and virgin soils with accumulations not evident in the tillage pans. From the Si extracted, there was an accumulation of Si in the tillage pan. The 0.5N NaOH was found to dissolve gibbsite, in addition to amorphous Al compounds. This was confirmed by DTA and X-ray analysis. The extractable Al was higher from the tillage pans than at

corresponding depths of virgin soil. The increased amounts of Si, Al, and Fe in the tillage pans were indicative that cementation compounds might be Fe or Al silicates. The molar ratios for Fe/Si, Al/Si, and Fe/Al averaged 1.0, 2.5, and 0.4, respectively. This indicated that more Al than Fe was extracted and that silicates were likely to be combined with Fe and Al in the cementation materials.

Except for variation in gibbsite content, the clays in the tillage pans were similar between soil series, within the profile, and to corresponding depths of virgin soil. There was an apparent increase in crystallinity of kaolinite in cultivated soils.

The pH and the acetate extractable Ca, Mg, K, and P increased in the cultivated soils compared to the virgin counterparts. Some evidence was found that the fertility of tillage pans was increased by the accumulation of ions that leached from above the pan.

Roots of field corn, Pensacola bahiagrass, Bermudagrass, cotton, and soybeans either failed to penetrate the tillage pans or were distorted in the pan. Lateral root growth was much restricted in the pan compared to that observed above or below the pan. Distortions of the epidermis and interior of the roots were noted from microscopic study of young root sections. This indicated that growth was restricted by the soil strength and small pores. Chemical analysis of the soil and roots did not indicate a nutrient deficiency. However, the roots were high in Si, Al, and Fe; some deposition of solids was noted in the cortical tissue.

From thin section studies, the tillage pan showed a compressed fabric lacking in the large pore spaces found above or below the pan, or in the virgin soil. This evidence coupled with the significant changes

in soil strength, bulk density, and pore space found in the tillage pans indicated development of an unfavorable physical medium for root penetration and growth. These selected Coastal Plain soils developed tillage pans which were quite similar in physical properties and in the unfavorable effect on root growth.

APPENDIX

Table 12 -- Sites, soil series, and location of soils sampled for tillage pan characterization and root studies

| Site no.* | Soil series | Locations in Florida |
|-----------|-------------|---|
| 1 | Norfolk | SE $\frac{1}{4}$ of section 8, T. 2 N., R. 2 W., Gadsden Co. |
| 2 | Norfolk | NE $\frac{1}{4}$ of section 29, T. 2 N., R. 4 W., Gadsden Co. |
| 3 | Norfolk | NW $\frac{1}{4}$ of section 26, T. 5 N., R. 13 W., Washington Co. |
| 4 | Norfolk | NE $\frac{1}{4}$ of section 32, T. 4 N., R. 15 W., Washington Co. |
| 5 | Norfolk | SE $\frac{1}{4}$ of section 11, T. 2 N., R. 32 W., Escambia Co. |
| 6 | Norfolk | West Florida Experiment Station, Santa Rosa Co. |
| 7 | Red Bay | NE $\frac{1}{4}$ of section 9, T. 2 N., R. 4 W., Gadsden Co. |
| 8 | Red Bay | SE $\frac{1}{4}$ of section 16, T. 2 N., R. 4 W., Gadsden Co. |
| 9 | Red Bay | SW $\frac{1}{4}$ of section 19, T. 2 N., R. 4 W., Gadsden Co. |
| 10 | Red Bay | SW $\frac{1}{4}$ of section 5, T. 3 N., R. 32 W., Escambia Co. |
| 11 | Red Bay | NE $\frac{1}{4}$ of section 9, T. 5 N., R. 32 W., Escambia Co. |
| 12 | Red Bay | West Florida Experiment Station, Santa Rosa Co. |
| 13 | Orangeburg | NE $\frac{1}{4}$ of section 5, T. 4 N., R. 12 W., Washington Co. |
| 14 | Orangeburg | NW $\frac{1}{4}$ of section 5, T. 3 N., R. 12 W., Washington Co. |
| 15 | Lakeland | NE $\frac{1}{4}$ of section 21, T. 2 N., R. 4 W., Gadsden Co. |
| 16 | Lakeland | NE $\frac{1}{4}$ of section 14, T. 2 N., R. 6 W., Gadsden Co. |
| 17 | Lakeland | SW $\frac{1}{4}$ of section 32, T. 4 N., R. 15 W., Washington Co. |
| 18 | Lakeland | NW $\frac{1}{4}$ of section 30, T. 4 N., R. 12 W., Washington Co. |
| 19 | Lakeland | SW $\frac{1}{4}$ of section 11, T. 2 N., R. 32 W., Escambia Co. |
| 20 | Lakeland | SE $\frac{1}{4}$ of section 19, T. 3 N., R. 32 W., Escambia Co. |

* The site number remains the same in Tables 12 to 26 with the exception of Table 16 which groups the soils by counties.

Table 13 -- Soil strengths measured by the pocket penetrometer and bulk densities of selected Coastal Plain soils

| Site no. | Depth | Penetrometer reading | | Bulk density | |
|-----------------------|--------------|------------------------------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| | ---- cm ---- | ---- kg/cm ² ---- | | ---- g/cc ---- | |
| <u>Norfolk series</u> | | | | | |
| 1 | 0-18 | 0.75 | 0.50 | 1.43 | 1.26 |
| | 18-36 | 2.75 | 1.50 | 1.67 | 1.47 |
| | 36-54 | 1.50 | 2.00 | 1.50 | 1.50 |
| 2 | 0-15 | 0.50 | 0.50 | 1.47 | 1.51 |
| | 15-30 | 2.00 | 1.50 | 1.72 | 1.54 |
| | 30-45 | 0.50 | 0.75 | 1.60 | 1.60 |
| 3 | 0-13 | 1.50 | 0.50 | 1.46 | 1.32 |
| | 13-26 | 2.75 | 0.50 | 1.64 | 1.45 |
| | 26-39 | 2.00 | 1.50 | 1.61 | 1.60 |
| 4 | 0-15 | 1.25 | 1.50 | 1.51 | 1.44 |
| | 15-25 | 2.75 | 0.75 | 1.60 | 1.46 |
| | 25-45 | 1.50 | 0.75 | 1.58 | 1.50 |
| 5 | 0-15 | 1.00 | 0.75 | 1.50 | 1.11 |
| | 15-30 | 3.50 | 1.50 | 1.52 | 1.39 |
| | 30-45 | 2.00 | 1.50 | 1.50 | 1.59 |
| 6 | 0-15 | 1.75 | 0.75 | 1.56 | 1.32 |
| | 15-30 | 3.50 | 2.25 | 1.65 | 1.45 |
| | 30-45 | 2.00 | 1.50 | 1.63 | 1.58 |
| <u>Red Bay series</u> | | | | | |
| 7 | 0-8 | 1.00 | 0.50 | 1.57 | 1.29 |
| | 8-16 | 3.50 | 1.50 | 1.66 | 1.51 |
| | 16-32 | 1.50 | 1.50 | 1.56 | 1.54 |
| 8 | 0-15 | 0.50 | 0.75 | 1.37 | 1.42 |
| | 15-30 | 3.00 | 1.25 | 1.62 | 1.54 |
| | 30-45 | 1.50 | 2.00 | 1.51 | 1.46 |
| 9 | 0-13 | 2.00 | 0.25 | 1.50 | 1.27 |
| | 13-26 | 3.50 | 1.00 | 1.60 | 1.41 |
| | 26-39 | 1.50 | 1.00 | 1.57 | 1.55 |
| 10 | 0-8 | 1.50 | 1.50 | 1.10 | 1.26 |
| | 8-22 | 4.00 | 2.25 | 1.50 | 1.38 |
| | 22-38 | 1.50 | 1.75 | 1.27 | 1.32 |

Table 13 -- Continued

| Site no. | Depth | Penetrometer reading | | Bulk density | |
|--------------------------|--------------|------------------------------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| | ---- cm ---- | ---- kg/cm ² ---- | | ---- g/cc ---- | |
| 11 | 0-13 | 2.50 | 1.25 | 1.55 | 1.50 |
| | 13-30 | 3.75 | 1.75 | 1.61 | 1.49 |
| | 30-45 | 2.50 | 2.00 | 1.56 | 1.44 |
| 12 | 0-8 | 2.00 | 2.50 | 1.33 | 1.33 |
| | 8-25 | 4.00 | 1.50 | 1.60 | 1.46 |
| | 25-38 | 2.00 | 2.00 | 1.53 | 1.54 |
| <u>Orangeburg series</u> | | | | | |
| 13 | 0-13 | 0.75 | 1.00 | 1.59 | 1.39 |
| | 13-25 | 3.00 | 1.50 | 1.71 | 1.46 |
| | 25-45 | 2.00 | 2.50 | 1.60 | 1.50 |
| 14 | 0-15 | 1.50 | 0.75 | 1.56 | 1.42 |
| | 15-28 | 3.25 | 1.00 | 1.59 | 1.51 |
| | 28-45 | 2.25 | 1.50 | 1.52 | 1.47 |
| <u>Lakeland series</u> | | | | | |
| 15 | 0-8 | 2.00 | 0.25 | 1.50 | 1.27 |
| | 8-25 | 3.50 | 1.00 | 1.60 | 1.41 |
| | 25-45 | 1.50 | 1.00 | 1.57 | 1.55 |
| 16 | 0-15 | 0.50 | 0.50 | 1.57 | 1.48 |
| | 15-30 | 2.00 | 0.25 | 1.70 | 1.50 |
| | 30-45 | 0.25 | 0.25 | 1.61 | 1.58 |
| 17 | 0-13 | 1.75 | 0.75 | 1.53 | 1.27 |
| | 13-20 | 2.50 | 1.00 | 1.55 | 1.32 |
| | 20-38 | 0.75 | 0.75 | 1.53 | 1.45 |
| 18 | 0-18 | 0.50 | 0.25 | 1.47 | 1.30 |
| | 18-30 | 1.75 | 0.25 | 1.65 | 1.40 |
| | 30-50 | 1.00 | 0.25 | 1.55 | 1.48 |
| 19 | 0-18 | 1.25 | 1.50 | 1.45 | 1.41 |
| | 18-30 | 3.50 | 0.75 | 1.63 | 1.41 |
| | 30-43 | 2.25 | 0.50 | 1.61 | 1.40 |
| 20 | 0-10 | 1.25 | 0.75 | 1.50 | 1.34 |
| | 10-28 | 3.50 | 1.25 | 1.64 | 1.55 |
| | 28-50 | 0.75 | 0.50 | 1.57 | 1.46 |

Table 14 -- Particle densities and porosities (total pore space) of selected Coastal Plain soils

| Site no. | Depth | Particle density | | Porosity | |
|-----------------------|-------|------------------|-------|-------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| ---- cm ---- | | ---- g/cc ---- | | ---- % ---- | |
| <u>Norfolk series</u> | | | | | |
| 1 | 0-18 | 2.68 | 2.65 | 47.2 | 52.5 |
| | 18-36 | 2.70 | 2.65 | 38.4 | 44.5 |
| | 36-54 | 2.71 | 2.70 | 44.4 | 44.4 |
| 2 | 0-15 | 2.68 | 2.68 | 45.4 | 44.1 |
| | 15-30 | 2.69 | 2.69 | 35.6 | 46.3 |
| | 30-45 | 2.70 | 2.70 | 41.7 | 39.3 |
| 3 | 0-13 | 2.62 | 2.65 | 44.3 | 52.0 |
| | 13-26 | 2.68 | 2.67 | 39.2 | 47.5 |
| | 26-39 | 2.73 | 2.74 | 41.0 | 41.6 |
| 4 | 0-15 | 2.69 | 2.69 | 44.1 | 46.5 |
| | 15-25 | 2.70 | 2.68 | 41.6 | 45.5 |
| | 25-45 | 2.74 | 2.73 | 41.3 | 45.1 |
| 5 | 0-15 | 2.66 | 2.70 | 49.2 | 59.2 |
| | 15-30 | 2.67 | 2.72 | 44.0 | 49.5 |
| | 30-45 | 2.72 | 2.76 | 45.0 | 41.7 |
| 6 | 0-15 | 2.68 | 2.64 | 42.9 | 50.0 |
| | 15-30 | 2.71 | 2.65 | 38.2 | 45.3 |
| | 30-45 | 2.70 | 2.73 | 39.6 | 42.1 |
| <u>Red Bay series</u> | | | | | |
| 7 | 0-8 | 2.62 | 2.60 | 40.1 | 50.4 |
| | 8-16 | 2.68 | 2.68 | 38.1 | 43.7 |
| | 16-32 | 2.69 | 2.61 | 42.0 | 41.0 |
| 8 | 0-15 | 2.60 | 2.61 | 47.3 | 45.6 |
| | 15-30 | 2.67 | 2.70 | 39.3 | 43.0 |
| | 30-45 | 2.63 | 2.68 | 42.6 | 45.5 |
| 9 | 0-13 | 2.61 | 2.57 | 41.4 | 48.2 |
| | 13-26 | 2.65 | 2.64 | 36.2 | 40.2 |
| | 26-39 | 2.63 | 2.66 | 39.5 | 41.8 |
| 10 | 0-8 | 2.67 | 2.65 | 59.6 | 52.5 |
| | 8-22 | 2.68 | 2.69 | 43.8 | 48.7 |
| | 22-38 | 2.71 | 2.68 | 53.1 | 50.8 |

Table 14 -- Continued

| Site no. | Depth | <u>Particle density</u> | | <u>Porosity</u> | |
|--------------------------|--------------|-------------------------|-------|-----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| | ---- cm ---- | ---- g/cc ---- | | ----- % ----- | |
| 11 | 0-13 | 2.69 | 2.69 | 42.4 | 44.2 |
| | 13-30 | 2.70 | 2.68 | 40.4 | 44.4 |
| | 30-45 | 2.67 | 2.73 | 41.6 | 47.3 |
| 12 | 0- 8 | 2.66 | 2.68 | 50.0 | 50.4 |
| | 8-25 | 2.70 | 2.72 | 40.5 | 46.3 |
| | 25-38 | 2.71 | 2.71 | 43.5 | 43.2 |
| <u>Orangeburg series</u> | | | | | |
| 13 | 0-13 | 2.64 | 2.67 | 39.8 | 48.7 |
| | 13-25 | 2.70 | 2.68 | 36.7 | 46.1 |
| | 25-35 | 2.75 | 2.74 | 41.8 | 45.2 |
| 14 | 0-15 | 2.70 | 2.68 | 42.9 | 45.0 |
| | 15-28 | 2.70 | 2.68 | 41.1 | 43.7 |
| | 28-45 | 2.72 | 2.71 | 44.2 | 45.8 |
| <u>Lakeland series</u> | | | | | |
| 15 | 0- 8 | 2.58 | 2.65 | 41.9 | 51.3 |
| | 8-25 | 2.65 | 2.63 | 39.6 | 46.4 |
| | 25-45 | 2.71 | 2.66 | 42.1 | 41.7 |
| 16 | 0-15 | 2.68 | 2.68 | 41.8 | 45.2 |
| | 15-30 | 2.65 | 2.70 | 35.6 | 44.5 |
| | 30-45 | 2.70 | 2.70 | 40.0 | 41.3 |
| 17 | 0-13 | 2.70 | 2.70 | 44.2 | 53.5 |
| | 13-20 | 2.73 | 2.70 | 43.2 | 51.1 |
| | 20-38 | 2.70 | 2.71 | 43.3 | 46.5 |
| 18 | 0-18 | 2.70 | 2.69 | 46.6 | 51.7 |
| | 18-30 | 2.71 | 2.70 | 40.0 | 48.1 |
| | 30-50 | 2.69 | 2.70 | 42.4 | 45.2 |
| 19 | 0-18 | 2.71 | 2.70 | 46.5 | 47.8 |
| | 18-30 | 2.73 | 2.68 | 40.3 | 47.4 |
| | 30-43 | 2.73 | 2.72 | 41.0 | 48.5 |
| 20 | 0-10 | 2.71 | 2.68 | 44.7 | 49.4 |
| | 10-28 | 2.68 | 2.74 | 38.8 | 43.4 |
| | 28-50 | 2.70 | 2.72 | 43.3 | 45.6 |

Table 15 -- Particle size distribution of selected Coastal Plain soils

| Site no. | Depth | Sand | | Silt | | Clay | |
|-----------------------|-------|---------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- % ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 88.9 | 86.7 | 7.3 | 8.6 | 3.8 | 4.7 |
| | 18-36 | 78.3 | 84.1 | 9.7 | 10.2 | 12.0 | 5.7 |
| | 36-54 | 61.3 | 66.0 | 8.5 | 9.2 | 30.2 | 24.8 |
| 2 | 0-15 | 92.2 | 81.7 | 5.1 | 13.3 | 2.7 | 5.0 |
| | 15-36 | 88.8 | 80.2 | 6.7 | 14.0 | 4.5 | 5.8 |
| | 30-45 | 79.2 | 79.2 | 12.9 | 13.3 | 7.9 | 6.9 |
| 3 | 0-13 | 88.8 | 90.3 | 5.7 | 7.1 | 5.5 | 2.6 |
| | 13-26 | 86.6 | 83.5 | 7.1 | 7.3 | 6.3 | 9.2 |
| | 26-39 | 66.0 | 67.1 | 6.0 | 8.7 | 28.0 | 24.2 |
| 4 | 0-15 | 89.5 | 83.2 | 7.5 | 11.6 | 3.1 | 5.2 |
| | 15-25 | 85.3 | 81.0 | 9.2 | 12.0 | 5.5 | 7.0 |
| | 25-45 | 80.6 | 78.2 | 9.2 | 12.2 | 10.2 | 9.6 |
| 5 | 0-15 | 64.4 | 66.7 | 24.4 | 25.5 | 11.5 | 7.8 |
| | 15-30 | 67.8 | 67.3 | 22.6 | 26.5 | 9.6 | 6.2 |
| | 30-45 | 52.4 | 54.6 | 23.5 | 27.6 | 24.0 | 17.8 |
| 6 | 0-15 | 76.9 | 79.2 | 15.5 | 14.4 | 7.6 | 6.4 |
| | 15-30 | 74.2 | 74.9 | 15.8 | 15.2 | 10.0 | 9.9 |
| | 30-45 | 70.8 | 67.1 | 16.8 | 16.0 | 13.4 | 16.8 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 81.4 | 87.5 | 9.1 | 9.7 | 9.5 | 2.8 |
| | 8-16 | 68.0 | 85.2 | 9.2 | 9.4 | 22.8 | 5.4 |
| | 16-32 | 55.4 | 65.2 | 6.7 | 9.3 | 37.9 | 25.4 |
| 8 | 0-15 | 83.5 | 74.0 | 7.8 | 13.2 | 8.7 | 12.8 |
| | 15-30 | 77.6 | 76.3 | 8.5 | 7.1 | 13.9 | 16.6 |
| | 30-45 | 59.6 | 66.8 | 6.9 | 7.0 | 33.6 | 26.2 |
| 9 | 0-13 | 86.5 | 86.1 | 8.9 | 9.9 | 4.5 | 4.0 |
| | 13-26 | 82.4 | 85.7 | 10.1 | 9.5 | 7.4 | 4.8 |
| | 26-39 | 77.4 | 79.8 | 9.8 | 10.8 | 12.8 | 9.4 |
| 10 | 0- 8 | 86.5 | 87.4 | 10.7 | 9.8 | 2.8 | 2.8 |
| | 8-22 | 54.3 | 57.4 | 26.5 | 25.9 | 19.2 | 16.7 |
| | 22-38 | 50.4 | 51.7 | 23.9 | 24.3 | 25.7 | 24.1 |

Table 15 -- Continued

| Site no. | Depth | Sand | | Silt | | Clay | |
|-------------------|-------|---------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- % ----- | | | | | |
| 11 | 0-13 | 80.6 | 77.7 | 14.5 | 15.9 | 4.9 | 6.4 |
| | 13-30 | 77.2 | 75.1 | 16.2 | 16.9 | 6.6 | 8.0 |
| | 30-45 | 69.4 | 73.2 | 20.8 | 17.0 | 9.8 | 9.8 |
| 12 | 0- 8 | 63.7 | 62.6 | 19.4 | 22.2 | 16.4 | 15.2 |
| | 8-25 | 59.9 | 57.1 | 21.8 | 21.3 | 18.3 | 21.6 |
| | 25-38 | 50.8 | 57.0 | 15.1 | 15.9 | 34.0 | 24.1 |
| Orangeburg series | | | | | | | |
| 13 | 0-13 | 85.3 | 77.0 | 9.2 | 13.0 | 5.5 | 9.5 |
| | 13-25 | 81.8 | 75.5 | 10.5 | 11.9 | 7.7 | 12.6 |
| | 25-35 | 66.0 | 57.9 | 11.5 | 9.2 | 22.0 | 32.9 |
| 14 | 0-15 | 83.6 | 82.7 | 9.3 | 8.7 | 7.2 | 8.6 |
| | 15-28 | 72.6 | 70.3 | 13.0 | 9.3 | 14.5 | 20.4 |
| | 28-45 | 65.5 | 57.1 | 10.5 | 8.9 | 24.0 | 34.0 |
| Lakeland series | | | | | | | |
| 15 | 0- 8 | 89.1 | 94.9 | 7.7 | 3.4 | 3.1 | 1.7 |
| | 8-25 | 88.3 | 90.0 | 8.0 | 6.7 | 3.7 | 3.3 |
| | 25-45 | 88.1 | 91.6 | 7.2 | 5.8 | 4.7 | 2.6 |
| 16 | 0-15 | 94.4 | 94.8 | 4.2 | 4.3 | 1.4 | 0.9 |
| | 15-30 | 94.2 | 94.6 | 4.2 | 3.8 | 1.6 | 1.5 |
| | 30-45 | 93.8 | 94.4 | 4.4 | 4.1 | 1.8 | 1.6 |
| 17 | 0-13 | 90.9 | 90.7 | 5.8 | 7.2 | 3.3 | 2.1 |
| | 13-20 | 90.5 | 90.1 | 5.8 | 7.5 | 3.7 | 2.4 |
| | 20-38 | 85.3 | 90.2 | 6.5 | 7.2 | 8.2 | 2.6 |
| 18 | 0-18 | 93.5 | 90.4 | 4.8 | 7.0 | 1.7 | 2.6 |
| | 18-30 | 92.0 | 92.4 | 5.3 | 5.5 | 2.7 | 2.1 |
| | 30-50 | 92.2 | 92.4 | 5.0 | 5.3 | 2.8 | 2.3 |
| 19 | 0-18 | 73.4 | 74.2 | 21.5 | 21.2 | 5.1 | 4.6 |
| | 18-30 | 73.4 | 74.0 | 20.7 | 20.4 | 5.9 | 5.4 |
| | 30-43 | 73.3 | 74.0 | 20.8 | 18.8 | 5.9 | 7.0 |
| 20 | 0-10 | 86.0 | 85.8 | 11.2 | 11.1 | 2.8 | 2.1 |
| | 10-28 | 88.1 | 87.6 | 9.5 | 9.7 | 2.4 | 2.7 |
| | 28-50 | 86.3 | 82.1 | 10.9 | 11.3 | 2.8 | 6.6 |

Table 16 -- Effect of fineness of texture on some physical properties of tillage pans in three counties and the corresponding analysis of variance

| County | Texture | | | | |
|---|----------|-------------|--------------|-----------|--------|
| | Coarsest | Less Coarse | Intermediate | Less fine | Finest |
| <u>Soil strength, kg/cm²</u> | | | | | |
| Gadsden | 3.50 | 2.00 | 2.75 | 3.00 | 3.50 |
| Washington | 2.50 | 2.75 | 2.75 | 3.00 | 3.25 |
| Escambia | 3.50 | 3.50 | 3.75 | 3.50 | 4.00 |
| <u>Bulk density, g/cc</u> | | | | | |
| Gadsden | 1.70 | 1.72 | 1.67 | 1.62 | 1.66 |
| Washington | 1.55 | 1.60 | 1.64 | 1.71 | 1.59 |
| Escambia | 1.64 | 1.63 | 1.61 | 1.52 | 1.50 |
| <u>Porosity, % of soil volume</u> | | | | | |
| Gadsden | 35.6 | 35.6 | 38.4 | 39.3 | 38.1 |
| Washington | 43.2 | 41.6 | 39.2 | 36.7 | 41.1 |
| Escambia | 38.8 | 40.3 | 40.4 | 44.0 | 43.8 |

Analysis of Variance

| Factor | Degrees of freedom | Sum of squares | Mean square | F value |
|----------------------|--------------------|----------------|-------------|---------|
| <u>Soil strength</u> | | | | |
| Counties | 2 | 1.90 | 0.95 | 7.30* |
| Textures | 4 | 1.06 | 0.27 | 2.10 |
| Error | 8 | 1.01 | 0.13 | |
| Total | 14 | 3.97 | | |
| <u>Bulk density</u> | | | | |
| Counties | 2 | 0.025 | 0.012 | 4.00 |
| Textures | 4 | 0.008 | 0.002 | 0.67 |
| Error | 8 | 0.027 | 0.003 | |
| Total | 14 | 0.060 | | |
| <u>Porosity</u> | | | | |
| Counties | 2 | 44.1 | 22.5 | 3.57 |
| Textures | 4 | 7.3 | 1.8 | 0.29 |
| Error | 8 | 50.7 | 6.3 | |
| Total | 14 | 102.1 | | |

* Significant at the 5% level.

Table 17 -- The soil reactions and organic matter contents of selected Coastal Plain soils

| Site no. | Depth | Soil reaction | | Organic matter | |
|----------|------------|-----------------------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| | --- cm --- | --- pH --- | | ---- % ---- | |
| | | <u>Norfolk series</u> | | | |
| 1 | 0-18 | 5.10 | 5.00 | 1.30 | 1.40 |
| | 18-36 | 5.00 | 5.08 | 0.54 | 0.78 |
| | 36-54 | 5.36 | 5.16 | 0.40 | 0.36 |
| 2 | 0-15 | 5.00 | 4.90 | 0.79 | 1.86 |
| | 15-30 | 5.25 | 5.15 | 1.66 | 0.30 |
| | 30-45 | 5.00 | 5.25 | 0.62 | 0.11 |
| 3 | 0-15 | 6.73 | 4.95 | 2.72 | 1.39 |
| | 13-26 | 6.66 | 5.28 | 0.84 | 0.65 |
| | 26-39 | 4.83 | 5.20 | 0.61 | 0.56 |
| 4 | 0-15 | 5.72 | 4.90 | 1.60 | 1.20 |
| | 15-25 | 5.15 | 5.15 | 0.67 | 0.67 |
| | 25-45 | 4.80 | 5.15 | 0.30 | 0.22 |
| 5 | 0-15 | 5.50 | 4.80 | 1.44 | 3.38 |
| | 15-30 | 5.65 | 5.00 | 1.67 | 0.88 |
| | 30-45 | 5.35 | 5.15 | 0.24 | 0.17 |
| 6 | 0-15 | 5.80 | 5.05 | 1.80 | 2.37 |
| | 15-30 | 6.08 | 5.25 | 1.22 | 1.20 |
| | 30-45 | 5.50 | 5.10 | 0.18 | 0.30 |
| | | <u>Red Bay series</u> | | | |
| 7 | 0- 8 | 6.13 | 6.39 | 1.60 | 2.07 |
| | 8-16 | 5.77 | 5.62 | 0.77 | 1.20 |
| | 16-32 | 5.73 | 5.08 | 0.34 | 0.58 |
| 8 | 0-15 | 5.38 | 5.77 | 1.56 | 3.08 |
| | 15-30 | 5.32 | 5.47 | 1.07 | 0.75 |
| | 30-45 | 5.82 | 5.30 | 0.34 | 0.39 |
| 9 | 0-13 | 5.80 | 5.08 | 1.92 | 3.05 |
| | 13-26 | 5.65 | 5.25 | 1.22 | 1.17 |
| | 26-39 | 5.34 | 5.33 | 0.26 | 0.28 |
| 10 | 0- 8 | 5.40 | 4.47 | 3.80 | 4.87 |
| | 8-22 | 5.35 | 5.20 | 2.96 | 1.76 |
| | 22-38 | 5.43 | 5.23 | 0.68 | 0.40 |

Table 17 -- Continued

| Site no. | Depth | Soil reaction | | Organic matter | |
|--------------------------|--------------|----------------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. |
| | ---- cm ---- | ----- pH ----- | | ----- % ----- | |
| 11 | 0-13 | 5.80 | 5.76 | 0.93 | 1.28 |
| | 13-30 | 5.75 | 5.70 | 0.54 | 0.40 |
| | 30-45 | 5.40 | 5.55 | 0.32 | 0.33 |
| 12 | 0- 8 | 5.05 | 5.25 | 4.88 | 4.15 |
| | 8-25 | 5.15 | 5.35 | 1.55 | 0.63 |
| | 25-38 | 5.55 | 5.05 | 0.34 | 0.23 |
| <u>Orangeburg series</u> | | | | | |
| 13 | 0-13 | 5.50 | 5.15 | 0.97 | 2.56 |
| | 13-25 | 5.00 | 5.05 | 0.97 | 1.33 |
| | 25-35 | 5.40 | 5.53 | 0.34 | 0.94 |
| 14 | 0-15 | 4.97 | 5.30 | 1.64 | 3.01 |
| | 15-38 | 4.05 | 4.95 | 1.64 | 1.58 |
| | 28-45 | 4.15 | 4.85 | 0.50 | 0.93 |
| <u>Lakeland series</u> | | | | | |
| 15 | 0- 8 | 6.72 | 4.88 | 2.11 | 1.00 |
| | 8-25 | 6.25 | 5.03 | 1.17 | 1.14 |
| | 25-45 | 5.40 | 5.72 | 0.27 | 0.44 |
| 16 | 0-15 | 4.20 | 4.42 | 0.69 | 0.99 |
| | 15-30 | 4.88 | 4.43 | 0.41 | 0.50 |
| | 30-45 | 5.10 | 4.70 | 0.17 | 0.11 |
| 17 | 0-13 | 4.93 | 4.63 | 1.18 | 1.84 |
| | 13-20 | 5.70 | 5.20 | 0.48 | 0.51 |
| | 20-38 | 5.90 | 5.05 | 0.21 | 0.38 |
| 18 | 0-18 | 5.53 | 5.05 | 0.91 | 1.27 |
| | 18-30 | 5.45 | 5.05 | 0.38 | 0.39 |
| | 30-50 | 5.24 | 5.10 | 0.18 | 0.24 |
| 19 | 0-18 | 5.50 | 4.90 | 1.58 | 1.81 |
| | 18-30 | 4.93 | 4.85 | 0.69 | 0.66 |
| | 30-43 | 4.70 | 5.05 | 0.08 | 0.34 |
| 20 | 0-10 | 5.40 | 4.67 | 0.81 | 1.77 |
| | 10-28 | 5.60 | 4.85 | 0.50 | 0.44 |
| | 28-50 | 5.50 | 5.00 | 0.16 | 0.22 |

Table 18 -- Aluminum, iron, and silicon extracted by hot peroxide extraction of selected Coastal Plain soils

| Site no. | Depth | Al | | Fe | | Si | |
|-----------------------|-------|-----------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- ppm ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 143 | 93 | 54 | 45 | 35 | 41 |
| | 18-36 | 62 | 103 | 7 | 26 | 20 | 32 |
| | 36-54 | 49 | 35 | 8 | 5 | 47 | 61 |
| 2 | 0-15 | 71 | 47 | 169 | 111 | 5 | 40 |
| | 15-30 | 45 | 127 | 5 | 144 | 3 | 44 |
| | 30-45 | 34 | 67 | 2 | 23 | 2 | 12 |
| 3 | 0-13 | 30 | 33 | 122 | 27 | 20 | 6 |
| | 13-26 | 37 | 67 | 4 | 11 | 16 | 9 |
| | 26-39 | 99 | 42 | 6 | 3 | 7 | 8 |
| 4 | 0-15 | 28 | 124 | 12 | 199 | 13 | 81 |
| | 15-25 | 110 | 91 | 10 | 8 | 16 | 36 |
| | 25-45 | 25 | 15 | 2 | 2 | 20 | 19 |
| 5 | 0-15 | 37 | 143 | 35 | 40 | 38 | 101 |
| | 15-30 | 40 | 86 | 19 | 33 | 43 | 30 |
| | 30-45 | 2 | 53 | 2 | 6 | 13 | 12 |
| 6 | 0-15 | 36 | 65 | 47 | 275 | 35 | 56 |
| | 15-30 | 97 | 65 | 20 | 57 | 37 | 28 |
| | 30-45 | 2 | 114 | 3 | 10 | 10 | 18 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 40 | 195 | 16 | 79 | 24 | 50 |
| | 8-16 | 57 | 40 | 14 | 64 | 43 | 8 |
| | 16-32 | 32 | 16 | 3 | 2 | 48 | 39 |
| 8 | 0-15 | 33 | 63 | 14 | 123 | 19 | 19 |
| | 15-30 | 83 | 70 | 7 | 20 | 7 | 31 |
| | 30-45 | 44 | 58 | 4 | 4 | 28 | 4 |
| 9 | 0-13 | 57 | 77 | 59 | 140 | 26 | 59 |
| | 13-26 | 51 | 30 | 33 | 117 | 14 | 5 |
| | 26-39 | 40 | 50 | 65 | 11 | 20 | 18 |
| 10 | 0- 8 | 94 | 209 | 59 | 128 | 42 | 98 |
| | 8-22 | 36 | 129 | 55 | 14 | 68 | 14 |
| | 22-38 | 20 | 10 | 1 | 5 | 58 | 14 |

Table 18 -- Continued

| Site no. | Depth | Al | | Fe | | Si | |
|--------------------------|-------|-----------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| --- cm --- | | ----- ppm ----- | | | | | |
| 11 | 0-13 | 48 | 130 | 23 | 57 | 12 | 20 |
| | 13-30 | 34 | 26 | 5 | 13 | 7 | 13 |
| | 30-45 | 3 | 10 | 10 | 10 | 12 | 14 |
| 12 | 0- 8 | 132 | 70 | 229 | 150 | 98 | 117 |
| | 8-25 | 20 | 70 | 1 | 4 | 14 | 62 |
| | 25-38 | 10 | 3 | 4 | 8 | 14 | 18 |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | 0-13 | 57 | 63 | 28 | 32 | 12 | 11 |
| | 13-25 | 22 | 52 | 9 | 43 | 6 | 18 |
| | 25-35 | 72 | 65 | 8 | 13 | 35 | 13 |
| 14 | 0-15 | 113 | 61 | 63 | 107 | 49 | 83 |
| | 15-28 | 87 | 195 | 48 | 40 | 50 | 48 |
| | 28-45 | 54 | 64 | 49 | 42 | 30 | 22 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | 0- 8 | 43 | 84 | 30 | 33 | 14 | 61 |
| | 8-25 | 78 | 63 | 54 | 32 | 16 | 11 |
| | 25-45 | 155 | 26 | 19 | 12 | 17 | 2 |
| 16 | 0-15 | 45 | 49 | 30 | 76 | 5 | 12 |
| | 15-30 | 33 | 30 | 10 | 15 | 2 | 3 |
| | 30-45 | 24 | 5 | 9 | 7 | 3 | 3 |
| 17 | 0-13 | 63 | 136 | 24 | 155 | 12 | 13 |
| | 13-20 | 40 | 83 | 23 | 22 | 5 | 8 |
| | 20-38 | 22 | 25 | 2 | 9 | 4 | 1 |
| 18 | 0-18 | 12 | 35 | 16 | 21 | 3 | 3 |
| | 18-30 | 18 | 12 | 16 | 4 | 2 | 3 |
| | 30-50 | 18 | 12 | 2 | 4 | 2 | 2 |
| 19 | 0-18 | 43 | 125 | 24 | 105 | 41 | 44 |
| | 18-30 | 81 | 61 | 32 | 7 | 24 | 14 |
| | 30-43 | 50 | 32 | 14 | 2 | 14 | 10 |
| 20 | 0-10 | 50 | 67 | 42 | 97 | 8 | 18 |
| | 10-28 | 56 | 28 | 11 | 1 | 9 | 3 |
| | 28-50 | 34 | 40 | 1 | 1 | 9 | 12 |

Table 19 -- Iron removed by citrate-dithionite extraction of selected Coastal Plain soils

| Site no. | Depth | Tillage | |
|-----------------------|-------|-----------------------------|-------|
| | | Cult. | Virg. |
| -- cm -- | | ----- mg Fe/g of soil ----- | |
| <u>Norfolk series</u> | | | |
| 1 | 0-18 | 1.29 | 1.78 |
| | 18-36 | 4.93 | 1.97 |
| | 36-54 | 10.20 | 7.90 |
| 2 | 0-15 | 1.10 | 1.35 |
| | 15-30 | 1.50 | 1.83 |
| | 30-45 | 1.81 | 1.89 |
| 3 | 0-13 | 1.88 | 1.28 |
| | 13-26 | 2.64 | 1.61 |
| | 26-39 | 9.21 | 11.70 |
| 4 | 0-15 | 1.07 | 2.45 |
| | 15-25 | 2.37 | 3.30 |
| | 25-45 | 5.08 | 5.52 |
| 5 | 0-15 | 3.13 | 2.44 |
| | 15-30 | 4.20 | 2.25 |
| | 30-45 | 8.83 | 10.80 |
| 6 | 0-15 | 2.99 | 2.71 |
| | 15-30 | 4.00 | 4.37 |
| | 30-45 | 5.87 | 6.75 |
| <u>Red Bay series</u> | | | |
| 7 | 0- 8 | 3.79 | 2.05 |
| | 8-16 | 10.20 | 2.00 |
| | 16-32 | 10.30 | 10.80 |
| 8 | 0-15 | 2.24 | 5.60 |
| | 15-30 | 6.65 | 7.76 |
| | 30-45 | 13.50 | 14.70 |
| 9 | 0-13 | 2.04 | 1.65 |
| | 13-26 | 4.88 | 3.53 |
| | 26-39 | 4.88 | 3.53 |
| 10 | 0- 8 | 1.70 | 6.42 |
| | 8-22 | 9.60 | 8.10 |
| | 22-38 | 14.50 | 12.70 |

Table 19 -- Continued

| Site no. | Depth | Tillage | |
|--------------------------|----------|-----------------------------|-------|
| | | Cult. | Virg. |
| | -- cm -- | ----- mg Fe/g of soil ----- | |
| 11 | 0-13 | 2.35 | 2.62 |
| | 13-30 | 3.03 | 4.24 |
| | 30-45 | 4.80 | 4.98 |
| 12 | 0- 8 | 12.90 | 8.00 |
| | 8-25 | 12.70 | 12.90 |
| | 25-38 | 12.00 | 14.10 |
| <u>Orangeburg series</u> | | | |
| 13 | 0-13 | 3.69 | 5.56 |
| | 13-25 | 5.45 | 7.53 |
| | 25-35 | 13.60 | 24.70 |
| 14 | 0-15 | 3.97 | 4.68 |
| | 15-28 | 7.42 | 8.24 |
| | 28-45 | 13.20 | 14.80 |
| <u>Lakeland series</u> | | | |
| 15 | 0- 8 | 1.38 | 0.62 |
| | 8-25 | 1.35 | 1.30 |
| | 25-45 | 1.88 | 1.25 |
| 16 | 0-15 | 0.67 | 0.41 |
| | 15-30 | 0.73 | 0.66 |
| | 30-45 | 0.87 | 0.81 |
| 17 | 0-13 | 1.76 | 0.79 |
| | 13-20 | 2.04 | 0.71 |
| | 20-38 | 4.49 | 1.71 |
| 18 | 0-18 | 0.71 | 1.28 |
| | 18-30 | 1.64 | 1.13 |
| | 30-50 | 1.45 | 1.62 |
| 19 | 0-18 | 2.03 | 1.44 |
| | 18-30 | 2.45 | 1.00 |
| | 30-43 | 2.22 | 3.12 |
| 20 | 0-10 | 1.82 | 1.70 |
| | 10-28 | 1.81 | 1.09 |
| | 28-50 | 2.02 | 6.29 |

Table 20 -- Aluminum extracted sequentially from selected Coastal Plain soils

| Site no. | Depth | Citrate-dithionite | | 0.5N NaOH | | Combined | |
|-----------------------|-------|-----------------------------|-------|-----------|-------|----------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- mg Al/g of soil ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 0.25 | 0.45 | 2.40 | 1.60 | 2.65 | 2.05 |
| | 18-36 | 1.11 | 0.48 | 4.33 | 2.40 | 5.44 | 2.88 |
| | 36-54 | 3.31 | 2.88 | 6.47 | 4.81 | 9.78 | 7.69 |
| 2 | 0-15 | 0.14 | 0.39 | 0.94 | 1.90 | 1.08 | 2.29 |
| | 15-30 | 0.38 | 0.50 | 0.69 | 1.41 | 1.07 | 1.91 |
| | 30-45 | 0.41 | 0.84 | 1.31 | 1.39 | 1.72 | 2.23 |
| 3 | 0-13 | 0.40 | 0.20 | 1.44 | 1.42 | 1.84 | 1.64 |
| | 13-26 | 0.66 | 0.33 | 3.73 | 1.87 | 4.39 | 2.10 |
| | 26-39 | 2.62 | 2.66 | 10.26 | 9.19 | 12.88 | 12.85 |
| 4 | 0-15 | 0.92 | 0.96 | 0.72 | 1.54 | 1.64 | 2.50 |
| | 15-25 | 1.39 | 1.41 | 1.86 | 1.98 | 3.37 | 3.39 |
| | 25-45 | 1.43 | 1.08 | 1.79 | 3.60 | 3.22 | 4.68 |
| 5 | 0-15 | 1.87 | 1.61 | 2.16 | 3.76 | 4.03 | 5.37 |
| | 15-30 | 4.22 | 1.84 | 1.78 | 2.56 | 6.00 | 4.40 |
| | 30-45 | 2.30 | 1.63 | 13.30 | 6.60 | 15.60 | 8.23 |
| 6 | 0-15 | 1.31 | 0.68 | 3.59 | 3.90 | 4.90 | 4.58 |
| | 15-30 | 1.57 | 1.59 | 5.47 | 6.40 | 7.04 | 7.99 |
| | 30-45 | 1.75 | 2.11 | 6.79 | 12.60 | 8.54 | 14.71 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 0.53 | 0.27 | 3.20 | 1.33 | 3.73 | 1.60 |
| | 8-16 | 1.85 | 0.33 | 10.40 | 2.67 | 12.25 | 3.00 |
| | 16-32 | 2.15 | 1.80 | 12.50 | 14.40 | 14.65 | 16.20 |
| 8 | 0-15 | 0.57 | 1.00 | 3.20 | 2.80 | 3.77 | 3.80 |
| | 15-30 | 0.95 | 1.39 | 7.97 | 6.75 | 8.92 | 8.14 |
| | 30-45 | 1.50 | 2.20 | 12.70 | 8.78 | 14.20 | 10.98 |
| 9 | 0-13 | 0.47 | 0.55 | 1.07 | 1.95 | 1.54 | 2.50 |
| | 13-26 | 0.70 | 0.47 | 2.18 | 2.14 | 2.88 | 2.61 |
| | 26-39 | 0.65 | 0.83 | 3.99 | 3.20 | 4.64 | 4.03 |
| 10 | 0- 8 | 1.14 | 1.72 | 1.88 | 1.78 | 3.02 | 3.50 |
| | 8-22 | 2.16 | 3.19 | 6.40 | 2.82 | 8.56 | 6.01 |
| | 22-38 | 1.90 | 4.50 | 17.40 | 6.07 | 19.30 | 10.57 |

Table 20 -- Continued

| Site no. | Depth | Citrate-dithionite | | 0.5N NaOH | | Combined | |
|--------------------------|-------|-----------------------------|-------|-----------|-------|----------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- mg Al/g of soil ----- | | | | | |
| 11 | 0-13 | 0.75 | 0.88 | 1.60 | 2.08 | 2.35 | 2.96 |
| | 13-30 | 1.04 | 0.72 | 2.38 | 3.25 | 3.42 | 3.97 |
| | 30-45 | 1.43 | 1.19 | 4.30 | 3.68 | 5.73 | 4.87 |
| 12 | 0- 8 | 2.40 | 2.18 | 13.80 | 9.57 | 16.20 | 11.75 |
| | 8-25 | 2.30 | 2.73 | 11.40 | 7.20 | 13.70 | 9.93 |
| | 25-38 | 1.85 | 2.08 | 26.90 | 12.60 | 28.75 | 14.68 |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | 0-13 | 0.60 | 1.04 | 1.06 | 1.67 | 1.66 | 2.71 |
| | 13-25 | 1.05 | 1.96 | 4.00 | 3.60 | 5.05 | 5.56 |
| | 25-35 | 2.94 | 4.48 | 4.58 | 12.10 | 7.52 | 16.58 |
| 14 | 0-15 | 0.90 | 0.89 | 5.20 | 6.39 | 6.10 | 7.28 |
| | 15-28 | 1.10 | 2.03 | 9.18 | 10.01 | 10.28 | 12.04 |
| | 28-45 | 1.97 | 1.94 | 22.05 | 28.45 | 24.02 | 30.39 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | 0- 8 | 0.35 | 0.18 | 1.20 | 1.20 | 1.55 | 1.38 |
| | 8-25 | 0.47 | 0.32 | 1.63 | 0.96 | 2.10 | 1.28 |
| | 25-45 | 0.54 | 0.34 | 1.60 | 1.28 | 2.14 | 1.62 |
| 16 | 0-15 | 0.20 | 0.11 | 0.75 | 0.29 | 0.95 | 0.40 |
| | 15-30 | 0.24 | 0.11 | 0.65 | 0.53 | 0.89 | 0.64 |
| | 30-45 | 0.28 | 0.20 | 0.63 | 0.94 | 0.91 | 1.14 |
| 17 | 0-13 | 0.54 | 0.22 | 0.83 | 0.60 | 1.37 | 0.82 |
| | 13-20 | 0.70 | 0.42 | 1.64 | 1.08 | 2.37 | 1.50 |
| | 20-38 | 1.26 | 0.35 | 2.80 | 1.36 | 4.06 | 1.71 |
| 18 | 0-18 | 0.27 | 0.34 | 1.07 | 1.59 | 1.34 | 1.93 |
| | 18-30 | 0.32 | 0.25 | 1.76 | 1.20 | 2.08 | 1.45 |
| | 30-50 | 0.35 | 0.43 | 1.60 | 2.59 | 1.95 | 3.02 |
| 19 | 0-18 | 1.00 | 1.62 | 2.30 | 3.58 | 3.30 | 5.20 |
| | 18-30 | 1.67 | 1.14 | 2.68 | 1.79 | 4.35 | 2.93 |
| | 30-43 | 2.17 | 1.73 | 2.28 | 2.50 | 4.45 | 4.23 |
| 20 | 0-10 | 0.64 | 1.06 | 1.53 | 1.55 | 2.17 | 2.61 |
| | 10-28 | 0.54 | 0.68 | 1.08 | 1.04 | 1.62 | 1.72 |
| | 28-50 | 0.48 | 1.84 | 1.40 | 3.06 | 1.88 | 4.90 |

Table 21 -- Silicon extracted sequentially from selected Coastal Plain soils

| Site no. | Depth | Citrate-dithionite | | 0.5N NaOH | | Combined value | |
|-----------------------|-------|-----------------------------|-------|-----------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- mg Si/g of soil ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 0.44 | 0.63 | 0.72 | 2.27 | 1.61 | 2.90 |
| | 18-36 | 0.68 | 0.29 | 2.51 | 1.00 | 3.19 | 1.29 |
| | 36-54 | 1.57 | 0.77 | 3.80 | 4.00 | 5.37 | 4.77 |
| 2 | 0-15 | 0.15 | 0.30 | 0.37 | 1.06 | 0.52 | 1.36 |
| | 15-30 | 0.31 | 0.29 | 0.56 | 0.82 | 0.87 | 1.11 |
| | 30-45 | 0.47 | 0.42 | 0.82 | 0.76 | 1.30 | 1.18 |
| 3 | 0-13 | 0.49 | 0.38 | 0.64 | 0.28 | 1.13 | 0.66 |
| | 13-26 | 0.81 | 0.80 | 1.07 | 0.21 | 1.88 | 1.01 |
| | 26-39 | 0.78 | 1.05 | 1.58 | 0.72 | 2.36 | 1.77 |
| 4 | 0-15 | 0.60 | 0.32 | 0.48 | 1.00 | 1.08 | 1.32 |
| | 15-25 | 0.58 | 0.63 | 1.08 | 2.16 | 1.66 | 2.79 |
| | 25-45 | 0.70 | 0.48 | 1.37 | 1.68 | 2.07 | 2.16 |
| 5 | 0-15 | 0.51 | 0.57 | 2.14 | 1.36 | 2.65 | 1.93 |
| | 15-30 | 0.28 | 0.42 | 1.64 | 1.23 | 1.92 | 1.65 |
| | 30-45 | 0.45 | 0.54 | 2.17 | 3.24 | 2.62 | 3.75 |
| 6 | 0-15 | 0.25 | 0.26 | 1.92 | 1.17 | 2.17 | 1.43 |
| | 15-30 | 0.24 | 0.35 | 1.62 | 1.36 | 1.86 | 1.71 |
| | 30-45 | 0.28 | 0.44 | 1.72 | 1.25 | 2.00 | 1.69 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 0.33 | 0.34 | 1.06 | 0.85 | 1.39 | 1.19 |
| | 8-16 | 1.90 | 0.42 | 4.15 | 0.85 | 6.05 | 1.27 |
| | 16-32 | 2.05 | 1.07 | 5.90 | 2.08 | 7.95 | 3.15 |
| 8 | 0-15 | 1.06 | 0.38 | 1.70 | 0.90 | 2.76 | 1.28 |
| | 15-30 | 1.07 | 1.19 | 2.14 | 2.06 | 3.21 | 3.25 |
| | 30-45 | 1.24 | 0.50 | 2.07 | 2.56 | 3.31 | 3.06 |
| 9 | 0-13 | 0.33 | 0.62 | 0.96 | 1.00 | 1.29 | 1.62 |
| | 13-26 | 0.87 | 0.73 | 1.76 | 1.13 | 2.63 | 1.86 |
| | 26-39 | 0.77 | 0.65 | 2.72 | 1.81 | 3.49 | 2.46 |
| 10 | 0- 8 | 0.33 | 0.16 | 0.32 | 1.57 | 0.65 | 1.73 |
| | 8-22 | 0.81 | 0.35 | 2.68 | 2.61 | 3.49 | 2.96 |
| | 22-38 | 0.39 | 0.39 | 3.00 | 3.67 | 3.39 | 4.06 |

Table 21 -- Continued

| Site no. | Depth | Citrate-dithionite | | 0.5N NaOH | | Combined value | |
|--------------------------|-------|-----------------------------|-------|-----------|-------|----------------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| --- cm --- | | ----- mg Si/g of soil ----- | | | | | |
| 11 | 0-13 | 0.26 | 0.20 | 0.72 | 1.20 | 0.98 | 1.40 |
| | 13-30 | 0.26 | 0.25 | 1.28 | 1.49 | 1.54 | 1.74 |
| | 30-45 | 0.45 | 0.53 | 2.71 | 1.60 | 3.16 | 2.13 |
| 12 | 0- 8 | 0.54 | 0.39 | 4.32 | 1.59 | 4.86 | 1.98 |
| | 8-25 | 0.58 | 0.40 | 2.29 | 3.25 | 2.87 | 3.65 |
| | 25-38 | 0.63 | 0.60 | 3.60 | 2.77 | 4.23 | 3.37 |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | 0-13 | 0.35 | 1.00 | 0.37 | 1.04 | 0.72 | 2.04 |
| | 13-25 | 0.78 | 1.29 | 1.20 | 1.49 | 1.98 | 2.78 |
| | 23-35 | 1.52 | 2.53 | 1.65 | 2.58 | 3.17 | 5.11 |
| 14 | 0-15 | 1.50 | 0.39 | 1.12 | 1.00 | 2.62 | 1.39 |
| | 15-28 | 1.47 | 0.50 | 3.04 | 1.36 | 4.51 | 1.86 |
| | 28-45 | 0.81 | 0.77 | 2.45 | 1.47 | 3.26 | 2.24 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | 0- 8 | 0.36 | 0.74 | 0.69 | 0.39 | 1.05 | 1.13 |
| | 8-25 | 0.45 | 0.60 | 0.73 | 0.45 | 1.18 | 1.15 |
| | 25-45 | 0.70 | 0.52 | 0.96 | 0.48 | 1.66 | 1.00 |
| 16 | 0-15 | 0.19 | 0.12 | 0.19 | 0.12 | 0.38 | 0.24 |
| | 15-30 | 0.16 | 0.15 | 0.27 | 0.08 | 0.43 | 0.23 |
| | 30-45 | 0.36 | 0.26 | 0.10 | 0.15 | 0.46 | 0.41 |
| 17 | 0-13 | 0.25 | 0.11 | 0.54 | 0.33 | 0.79 | 0.44 |
| | 13-20 | 0.27 | 0.08 | 0.55 | 0.31 | 0.82 | 0.39 |
| | 20-38 | 0.28 | 0.22 | 1.00 | 0.44 | 1.28 | 0.66 |
| 18 | 0-18 | 0.47 | 0.50 | 0.48 | 0.97 | 0.95 | 1.47 |
| | 18-30 | 0.48 | 0.44 | 0.32 | 0.52 | 0.80 | 0.96 |
| | 30-50 | 0.58 | 0.25 | 1.28 | 0.48 | 1.86 | 0.73 |
| 19 | 0-18 | 0.53 | 0.46 | 0.80 | 0.80 | 1.33 | 1.26 |
| | 18-30 | 0.71 | 0.33 | 0.84 | 0.32 | 1.55 | 0.65 |
| | 30-43 | 0.63 | 0.54 | 2.34 | 1.68 | 2.97 | 2.22 |
| 20 | 0-10 | 0.22 | 0.17 | 0.48 | 0.48 | 0.70 | 0.65 |
| | 10-28 | 0.20 | 0.33 | 0.42 | 0.46 | 0.61 | 0.79 |
| | 28-50 | 0.33 | 0.42 | 0.72 | 2.58 | 1.05 | 3.00 |

Table 22 -- Cations removed by extraction of selected Coastal Plain soils with acid ammonium acetate

| Site no. | Depth | Ca | | Mg | | K | |
|-----------------------|-------|-----------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- ppm ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 42 | 15 | 13 | 3 | 56 | 10 |
| | 18-36 | 70 | 11 | 13 | 3 | 18 | 4 |
| | 36-54 | 270 | 27 | 50 | 45 | 10 | 8 |
| 2 | 0-15 | 131 | 100 | 59 | 16 | 20 | 14 |
| | 15-30 | 70 | 56 | 20 | 16 | 26 | 6 |
| | 30-45 | 42 | 25 | 13 | 10 | 28 | 6 |
| 3 | 0-13 | 1250 | 27 | 55 | 3 | 98 | 20 |
| | 13-26 | 385 | 15 | 20 | 3 | 78 | 12 |
| | 26-39 | 132 | 70 | 26 | 7 | 96 | 12 |
| 4 | 0-15 | 289 | 27 | 20 | 13 | 46 | 22 |
| | 15-25 | 42 | 56 | 3 | 13 | 48 | 12 |
| | 25-45 | 27 | 56 | 5 | 3 | 12 | 10 |
| 5 | 0-15 | 309 | 27 | 41 | 5 | 136 | 16 |
| | 15-30 | 460 | 15 | 37 | 5 | 136 | 10 |
| | 30-45 | 289 | 27 | 55 | 13 | 92 | 10 |
| 6 | 0-15 | 429 | 56 | 26 | 16 | 122 | 20 |
| | 15-30 | 403 | 56 | 26 | 20 | 70 | 16 |
| | 30-45 | 182 | 27 | 16 | 20 | 42 | 10 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 441 | 149 | 107 | 50 | 86 | 26 |
| | 8-16 | 200 | 85 | 107 | 23 | 50 | 14 |
| | 16-32 | 309 | 85 | 81 | 59 | 22 | 30 |
| 8 | 0-15 | 654 | 115 | 190 | 23 | 94 | 50 |
| | 15-30 | 149 | 85 | 95 | 23 | 92 | 30 |
| | 30-45 | 27 | 32 | 85 | 10 | 34 | 14 |
| 9 | 0-13 | 289 | 100 | 37 | 35 | 158 | 30 |
| | 13-26 | 200 | 27 | 37 | 16 | 58 | 10 |
| | 26-39 | 100 | 27 | 35 | 8 | 88 | 8 |
| 10 | 0- 8 | 218 | 49 | 50 | 35 | 202 | 88 |
| | 8-22 | 183 | 42 | 30 | 41 | 72 | 48 |
| | 22-38 | 165 | 42 | 41 | 45 | 66 | 60 |

Table 22 -- Continued

| Site no. | Depth | Ca | | Mg | | K | |
|--------------------------|-------|-----------------|-------|-------|-------|-------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- ppm ----- | | | | | |
| 11 | 0-13 | 149 | 85 | 11 | 16 | 32 | 30 |
| | 13-30 | 182 | 100 | 33 | 16 | 22 | 20 |
| | 30-45 | 149 | 85 | 30 | 11 | 14 | 14 |
| 12 | 0- 8 | 165 | 70 | 41 | 20 | 80 | 48 |
| | 8-25 | 70 | 42 | 37 | 8 | 28 | 14 |
| | 25-38 | 23 | 15 | 30 | 30 | 26 | 10 |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | 0-13 | 85 | 65 | 41 | 8 | 42 | 42 |
| | 13-25 | 70 | 27 | 34 | 26 | 10 | 14 |
| | 25-35 | 149 | 27 | 30 | 14 | 16 | 12 |
| 14 | 0-15 | 200 | 15 | 69 | 5 | 52 | 30 |
| | 15-28 | 15 | 27 | 41 | 3 | 80 | 36 |
| | 28-45 | 42 | 27 | 64 | 5 | 50 | 42 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | 0- 8 | 654 | 27 | 73 | 13 | 28 | 16 |
| | 8-25 | 149 | 15 | 26 | 8 | 20 | 10 |
| | 25-45 | 27 | 27 | 16 | 5 | 22 | 8 |
| 16 | 0-15 | 10 | 10 | 3 | 3 | 10 | 10 |
| | 15-30 | 15 | 10 | 3 | 3 | 8 | 4 |
| | 30-45 | 15 | 10 | 3 | 3 | 8 | 4 |
| 17 | 0-13 | 115 | 42 | 20 | 8 | 30 | 20 |
| | 13-20 | 115 | 42 | 16 | 5 | 20 | 10 |
| | 20-38 | 42 | 27 | 37 | 5 | 38 | 10 |
| 18 | 0-18 | 42 | 15 | 5 | 3 | 38 | 14 |
| | 18-30 | 42 | 15 | 3 | 3 | 12 | 8 |
| | 30-50 | 27 | 15 | 3 | 3 | 8 | 6 |
| 19 | 0-18 | 149 | 15 | 35 | 5 | 76 | 14 |
| | 18-30 | 42 | 15 | 11 | 5 | 30 | 14 |
| | 30-43 | 27 | 12 | 5 | 2 | 28 | 14 |
| 20 | 0-10 | 27 | 15 | 5 | 3 | 10 | 12 |
| | 10-28 | 70 | 15 | 3 | 3 | 4 | 4 |
| | 28-50 | 70 | 10 | 5 | 3 | 8 | 4 |

Table 23 -- Endothermic area at three temperature ranges in the DTA patterns of clay from selected Coastal Plain soils

| Site no. | Depth | 50-150C | | 280-330C | | 525-600C | |
|-----------------------|-------|-------------------------------------|-------|----------|-------|----------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- %, total endotherm area ----- | | | | | |
| <u>Norfolk series</u> | | | | | | | |
| 1 | 0-18 | 22.0 | 9.7 | 7.5 | 7.1 | 70.5 | 83.1 |
| | 18-36 | 19.4 | 16.1 | 12.9 | 7.6 | 67.7 | 76.3 |
| | 36-54 | 23.0 | 16.4 | 10.4 | 9.0 | 66.6 | 74.6 |
| 2 | 0-15 | 13.9 | 0 | 34.7 | 17.2 | 51.4 | 81.8 |
| | 15-30 | 13.9 | 0 | 37.5 | 14.3 | 48.6 | 85.7 |
| | 30-45 | 14.8 | 0 | 33.8 | 21.0 | 51.4 | 79.0 |
| 3 | 0-13 | 29.6 | 28.6 | 14.8 | 21.4 | 55.6 | 50.0 |
| | 13-26 | 17.8 | 22.2 | 21.1 | 27.8 | 61.1 | 50.0 |
| | 26-39 | 17.4 | 15.8 | 24.4 | 36.8 | 58.2 | 47.4 |
| 4 | 0-15 | 25.5 | 29.2 | 13.2 | 17.7 | 61.3 | 53.1 |
| | 15-25 | 32.5 | 28.0 | 13.9 | 25.2 | 53.8 | 46.8 |
| | 25-45 | 21.4 | 22.4 | 14.3 | 27.6 | 64.3 | 47.9 |
| 5 | 0-15 | 13.0 | 18.2 | 43.5 | 31.8 | 43.5 | 50.0 |
| | 15-30 | 14.9 | 16.0 | 41.2 | 40.0 | 43.9 | 44.0 |
| | 30-45 | 10.7 | 11.5 | 44.6 | 52.8 | 44.6 | 35.6 |
| 6 | 0-15 | 13.3 | 0 | 66.7 | 78.9 | 20.0 | 21.1 |
| | 15-30 | 15.4 | 0 | 69.2 | 83.3 | 15.4 | 16.7 |
| | 30-45 | 10.5 | 0 | 66.4 | 82.9 | 23.1 | 17.1 |
| <u>Red Bay series</u> | | | | | | | |
| 7 | 0- 8 | 20.1 | 0 | 14.4 | 9.2 | 65.5 | 90.8 |
| | 8-16 | 14.1 | 0 | 18.8 | 16.5 | 67.1 | 83.5 |
| | 16-32 | 13.4 | 0 | 20.1 | 19.1 | 66.4 | 80.9 |
| 8 | 0-15 | 16.3 | 7.8 | 9.6 | 14.1 | 74.1 | 78.1 |
| | 15-30 | 14.0 | 8.2 | 14.0 | 24.0 | 72.0 | 67.8 |
| | 30-45 | 21.0 | 9.9 | 12.6 | 19.1 | 66.4 | 71.0 |
| 9 | 0-13 | 13.4 | 15.4 | 11.2 | 7.7 | 75.3 | 76.9 |
| | 13-26 | 16.1 | 19.1 | 9.1 | 7.4 | 74.8 | 73.5 |
| | 26-39 | 21.6 | 23.1 | 11.1 | 7.7 | 67.3 | 69.2 |
| 10 | 0- 8 | 18.2 | 27.2 | 54.5 | 18.4 | 27.3 | 54.4 |
| | 8-22 | 18.7 | 22.9 | 48.8 | 19.5 | 32.5 | 57.5 |
| | 22-38 | 13.9 | 18.5 | 49.2 | 22.2 | 36.9 | 59.3 |

Table 23 -- Continued

| Site no. | Depth | 50-150C | | 280-330C | | 525-600C | |
|--------------------------|-------|--------------------------------------|-------|----------|-------|----------|-------|
| | | Cult. | Virg. | Cult. | Virg. | Cult. | Virg. |
| -- cm -- | | ----- % , total endotherm area ----- | | | | | |
| 11 | 0-13 | 22.7 | 25.6 | 24.2 | 29.5 | 53.1 | 44.9 |
| | 13-30 | 26.7 | 21.0 | 33.3 | 36.8 | 40.0 | 42.1 |
| | 30-45 | 31.8 | 22.9 | 31.8 | 34.5 | 36.4 | 42.5 |
| 12 | 0- 8 | 7.8 | 15.0 | 72.3 | 65.4 | 19.9 | 19.6 |
| | 8-25 | 13.7 | 14.7 | 68.3 | 67.6 | 18.0 | 17.7 |
| | 25-38 | 7.5 | 11.7 | 75.1 | 74.3 | 17.3 | 14.3 |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | 0-13 | 23.1 | 24.8 | 15.7 | 22.6 | 61.5 | 52.6 |
| | 13-25 | 24.7 | 25.5 | 15.4 | 25.5 | 59.9 | 49.0 |
| | 25-35 | 22.1 | 22.2 | 16.4 | 27.8 | 61.5 | 50.0 |
| 14 | 0-15 | 12.3 | 0 | 52.5 | 57.1 | 35.2 | 42.9 |
| | 15-28 | 18.4 | 0 | 44.2 | 64.3 | 37.2 | 35.7 |
| | 28-45 | 14.5 | 0 | 49.4 | 58.8 | 36.1 | 41.2 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | 0- 8 | 15.0 | 18.7 | 11.8 | 15.9 | 73.5 | 65.7 |
| | 8-25 | 12.8 | 18.9 | 9.8 | 17.9 | 77.4 | 63.2 |
| | 25-45 | 13.9 | 19.3 | 12.0 | 16.1 | 74.1 | 64.6 |
| 16 | 0-15 | 23.5 | 20.0 | 53.0 | 53.3 | 23.5 | 26.6 |
| | 15-30 | 32.9 | 21.4 | 48.8 | 57.2 | 18.3 | 21.4 |
| | 30-45 | 18.2 | 29.2 | 63.6 | 58.3 | 18.2 | 12.5 |
| 17 | 0-13 | 0 | 18.7 | 17.5 | 56.3 | 82.5 | 25.0 |
| | 13-20 | 0 | 17.6 | 25.4 | 52.9 | 74.6 | 29.4 |
| | 20-38 | 0 | 16.0 | 33.3 | 64.0 | 66.7 | 20.0 |
| 18 | 0-18 | 27.2 | 19.2 | 34.0 | 46.2 | 38.8 | 34.6 |
| | 18-30 | 21.4 | 19.0 | 42.8 | 52.9 | 35.8 | 28.1 |
| | 30-50 | 18.4 | 21.0 | 49.0 | 49.7 | 32.5 | 29.2 |
| 19 | 0-18 | 23.8 | 17.0 | 28.6 | 48.0 | 47.6 | 35.0 |
| | 18-30 | 20.0 | 18.1 | 30.0 | 53.1 | 50.0 | 28.8 |
| | 30-43 | 22.2 | 15.5 | 38.8 | 61.9 | 38.8 | 22.6 |
| 20 | 0-10 | 20.2 | 16.1 | 65.5 | 59.1 | 14.3 | 24.7 |
| | 10-28 | 22.2 | 20.0 | 55.6 | 53.3 | 22.2 | 26.7 |
| | 28-50 | 17.9 | 19.2 | 58.0 | 38.4 | 24.1 | 42.3 |

Table 24 -- Aluminum and silicon removed from roots by treatment with hot 0.5N NaOH for 2 minutes

| Site no. | Crop | Root location | Al | Si |
|---------------------------|----------------------|---------------|-----|-----|
| -ppm, fresh root weight - | | | | |
| <u>Norfolk series</u> | | | | |
| 2 | Field corn | Above pan | 86 | 55 |
| | | In pan | 94 | 43 |
| | | Below pan | 115 | 34 |
| 3 | Bermudagrass | Above pan | 228 | 69 |
| | | In pan | 432 | 64 |
| | | Below pan | 429 | 72 |
| 4 | Pensacola bahiagrass | Above pan | 350 | 60 |
| | | In pan | 780 | 96 |
| | | Below pan | 414 | 146 |
| 5 | Field corn | Above pan | 195 | 54 |
| | | In pan | 469 | 88 |
| | | Below pan | - | - |
| 6 | Field corn | Above pan | 160 | 41 |
| | | In pan | 390 | 95 |
| | | Below pan | - | - |
| <u>Red Bay series</u> | | | | |
| 7 | Field corn | Above pan | 52 | 58 |
| | | In pan | 72 | 65 |
| | | Below pan | 82 | 72 |
| 8 | Field corn | Above pan | 160 | 41 |
| | | In pan | 490 | 69 |
| | | Below pan | 314 | 51 |
| 9 | Field corn | Above pan | 350 | 40 |
| | | In pan | 380 | 59 |
| | | Below pan | - | - |
| 10 | Field corn | Above pan | 94 | 39 |
| | | In pan | 112 | 65 |
| | | Below pan | - | - |
| 11 | Bermudagrass | Above pan | 140 | 96 |
| | | In pan | 158 | 81 |
| | | Below pan | 385 | 123 |

Table 24 -- Continued

| Site no. | Crop | Root location | Al | Si |
|---------------------------|----------------------|---------------|-----|-----|
| -ppm, fresh root weight - | | | | |
| <u>Orangeburg series</u> | | | | |
| 13 | Field corn | Above pan | 41 | 50 |
| | | In pan | 371 | 160 |
| | | Below pan | - | - |
| 14 | Field corn | Above pan | 242 | 42 |
| | | In pan | 300 | 63 |
| | | Below pan | - | - |
| <u>Lakeland series</u> | | | | |
| 15 | Pensacola bahiagrass | Above pan | 125 | 70 |
| | | In pan | 152 | 86 |
| | | Below pan | 350 | 84 |
| 16 | Field corn | Above pan | 155 | 70 |
| | | In pan | 200 | 96 |
| | | Below pan | 345 | 137 |
| 17 | Bermudagrass | Above pan | 122 | 35 |
| | | In pan | 140 | 49 |
| | | Below pan | 198 | 67 |
| 18 | Pensacola bahiagrass | Above pan | 310 | 32 |
| | | In pan | 455 | 59 |
| | | Below pan | 500 | 38 |
| 19 | Soybeans | Above pan | 162 | 82 |
| | | In pan | 285 | 97 |
| | | Below pan | - | - |

Table 25 -- Total aluminum, iron, and silicon of washed roots obtained from cultivated sites of selected Coastal Plain soils and showing the relationship to the tillage pan

| Site no. | Crop | Root location | Al | Fe | Si |
|-----------------------------|----------------------|---------------|-------|-------|-------|
| -- ppm, fresh root weight - | | | | | |
| <u>Norfolk series</u> | | | | | |
| 2 | Field corn | Above pan | 506 | 139 | 740 |
| | | In pan | 1,000 | 423 | 759 |
| | | Below pan | 1,530 | 510 | 1,214 |
| 3 | Bermudagrass | Above pan | 1,020 | 330 | 1,700 |
| | | In pan | 1,420 | 309 | 1,950 |
| | | Below pan | 1,890 | 513 | 2,210 |
| 4 | Pensacola bahiagrass | Above pan | 1,730 | 460 | 1,220 |
| | | In pan | 2,420 | 680 | 2,240 |
| | | Below pan | 2,410 | 857 | 1,800 |
| 5 | Field corn | Above pan | 1,370 | 590 | 920 |
| | | In pan | 1,890 | 792 | 1,160 |
| | | Below pan* | - | - | - |
| 6 | Field corn | Above pan | 429 | 1,210 | 1,690 |
| | | In pan | 708 | 1,900 | 1,370 |
| | | Below pan* | - | - | - |
| <u>Red Bay series</u> | | | | | |
| 7 | Field corn | Above pan | 1,240 | 330 | 776 |
| | | In pan | 2,090 | 537 | 1,370 |
| | | Below pan | 2,820 | 1,440 | 2,150 |
| 8 | Field corn | Above pan | 960 | 390 | 1,640 |
| | | In pan | 990 | 909 | 1,750 |
| | | Below pan | 1,600 | 395 | 2,380 |
| 9 | Field corn | Above pan | 1,600 | 410 | 2,060 |
| | | In pan | 2,150 | 854 | 2,840 |
| | | Below pan* | - | - | - |
| 10 | Field corn | Above pan | 1,270 | 500 | 1,660 |
| | | In pan | 1,140 | 340 | 548 |
| | | Below pan* | - | - | - |
| 11 | Bermudagrass | Above pan | 1,370 | 540 | 1,230 |
| | | In pan | 1,440 | 512 | 1,590 |
| | | Below pan | 1,250 | 392 | 1,090 |

Table 25 -- Continued

| Site no. | Crop | Root location | Al | Fe | Si |
|-----------------------------|----------------------|---------------|-------|-------|-------|
| -- ppm, fresh root weight - | | | | | |
| <u>Orangeburg series</u> | | | | | |
| 13 | Field corn | Above pan | 1,810 | 746 | 1,140 |
| | | In pan | 2,110 | 1,710 | 2,560 |
| | | Below pan | - | - | - |
| 14 | Field corn | Above pan | 1,650 | 375 | 880 |
| | | In pan | 1,900 | 720 | 1,460 |
| | | Below pan* | - | - | - |
| <u>Lakeland series</u> | | | | | |
| 15 | Pensacola bahiagrass | Above pan | 1,950 | 270 | 1,090 |
| | | In pan | 2,120 | 600 | 2,050 |
| | | Below pan | 2,180 | 730 | 2,120 |
| 16 | Field corn | Above pan | 710 | 270 | 328 |
| | | In pan | 1,310 | 286 | 409 |
| | | Below pan | 1,440 | 1,210 | 1,048 |
| 17 | Bermudagrass | Above pan | 1,660 | 439 | 880 |
| | | In pan | 1,850 | 540 | 1,250 |
| | | Below pan | 2,450 | 660 | 1,490 |
| 18 | Pensacola bahiagrass | Above pan | 1,430 | 370 | 1,110 |
| | | In pan | 1,960 | 703 | 2,250 |
| | | Below pan | 2,390 | 1,250 | 2,160 |
| 19 | Soybeans | Above pan | 1,110 | 392 | 760 |
| | | In pan | 2,080 | 1,310 | 1,770 |
| | | Below pan* | - | - | - |

* Roots were not found below the pan.

Table 26 -- Content of calcium, magnesium, and potassium in roots obtained from the cultivated sites of selected Coastal Plain soils and showing the relationship to the tillage pan

| Site no. | Crop | Root location | Ca | Mg | K |
|-----------------------------|----------------------|---------------|-------|-----|-------|
| -- ppm, fresh root weight - | | | | | |
| <u>Norfolk series</u> | | | | | |
| 2 | Field corn | Above pan | 350 | 61 | 1,450 |
| | | In pan | 236 | 319 | 1,400 |
| | | Below pan | 80 | 69 | 580 |
| 3 | Bermudagrass | Above pan | 350 | 159 | 1,650 |
| | | In pan | 124 | 52 | 330 |
| | | Below pan | 103 | 85 | 1,490 |
| 4 | Pensacola bahiagrass | Above pan | 100 | 35 | 880 |
| | | In pan | 241 | 96 | 1,080 |
| | | Below pan | 230 | 102 | 714 |
| 5 | Field corn | Above pan | 221 | 80 | 320 |
| | | In pan | 251 | 105 | 920 |
| | | Below pan* | - | - | - |
| 6 | Field corn | Above pan | 110 | 50 | 1,050 |
| | | In pan | 62 | 50 | 1,010 |
| | | Below pan* | - | - | - |
| <u>Red Bay series</u> | | | | | |
| 7 | Field corn | Above pan | 221 | 30 | 280 |
| | | In pan | 470 | 125 | 412 |
| | | Below pan | 1,220 | 207 | 400 |
| 8 | Field corn | Above pan | 161 | 58 | 900 |
| | | In pan | 477 | 183 | 1,180 |
| | | Below pan | 1,504 | 55 | 408 |
| 9 | Field corn | Above pan | 191 | 71 | 820 |
| | | In pan | 225 | 217 | 930 |
| | | Below pan* | - | - | - |
| 10 | Field corn | Above pan | 80 | 35 | 74 |
| | | In pan | 284 | 205 | 194 |
| | | Below pan* | - | - | - |
| 11 | Bermudagrass | Above pan | 261 | 117 | 1,180 |
| | | In pan | 196 | 152 | 1,660 |
| | | Below pan | 77 | 104 | 385 |

Table 26 -- Continued

| Site no. | Crop | Root location | Ca | Mg | K |
|-----------------------------|----------------------|---------------|-------|-----|-------|
| -- ppm, fresh root weight - | | | | | |
| <u>Orangeburg series</u> | | | | | |
| 13 | Field corn | Above pan | 647 | 285 | 1,490 |
| | | In pan | 431 | 316 | 1,280 |
| | | Below pan* | - | - | - |
| 14 | Field corn | Above pan | 84 | 60 | 694 |
| | | In pan | 261 | 90 | 500 |
| | | Below pan* | - | - | - |
| <u>Lakeland series</u> | | | | | |
| 15 | Pensacola bahiagrass | Above pan | 1,005 | 201 | 360 |
| | | In pan | 955 | 226 | 800 |
| | | Below pan | 352 | 137 | 720 |
| 16 | Field corn | Above pan | 80 | 49 | 800 |
| | | In pan | 36 | 53 | 700 |
| | | Below pan | 40 | 56 | 1,400 |
| 17 | Bermudagrass | Above pan | 196 | 91 | 683 |
| | | In pan | 201 | 121 | 873 |
| | | Below pan | 171 | 77 | 1,500 |
| 18 | Pensacola bahiagrass | Above pan | 330 | 212 | 960 |
| | | In pan | 458 | 222 | 850 |
| | | Below pan | 347 | 139 | 527 |
| 19 | Soybeans | Above pan | 380 | 123 | 973 |
| | | In pan | 420 | 210 | 850 |
| | | Below pan* | - | - | - |

* Roots were not found below the pan.

Table 27 -- Soil reaction, extractable cations, and phosphorus in soil samples taken relative to the tillage pan and roots from cultivated sites of selected Coastal Plain soils

| Site no. | Crop | Sample location | Soil reaction | Acid ammonium acetate extractable | | | |
|-----------------------|----------------------|-----------------|---------------|-----------------------------------|-----|-----|-----|
| | | | | Ca | Mg | K | P |
| --- pH --- | | | | ---- ppm ---- | | | |
| <u>Norfolk series</u> | | | | | | | |
| 2 | Field corn | Above pan | 5.5 | 215 | 5 | 32 | 22 |
| | | In pan | 5.7 | 116 | 5 | 30 | 6 |
| | | Below pan | 5.0 | 71 | 5 | 34 | 2 |
| 3 | Bermudagrass | Above pan | 5.7 | 437 | 16 | 52 | 24 |
| | | In pan | 5.8 | 170 | 6 | 34 | 16 |
| | | Below pan | 5.0 | 61 | 6 | 62 | 2 |
| 4 | Pensacola bahiagrass | Above pan | 5.8 | 104 | 8 | 22 | 4 |
| | | In pan | 5.8 | 71 | 8 | 14 | 2 |
| | | Below pan | 5.7 | 46 | 8 | 10 | 2 |
| 5 | Field corn | Above pan | 5.3 | 537 | 64 | 228 | 36 |
| | | In pan | 5.6 | 340 | 54 | 110 | 4 |
| | | Below pan* | --- | --- | --- | --- | --- |
| 6 | Field corn | Above pan | 5.1 | 290 | 26 | 170 | 36 |
| | | In pan | 5.4 | 150 | 23 | 74 | 2 |
| | | Below pan* | --- | --- | --- | --- | --- |
| <u>Red Bay series</u> | | | | | | | |
| 7 | Field corn | Above pan | 5.7 | 516 | 55 | 202 | 110 |
| | | In pan | 5.9 | 215 | 81 | 104 | 4 |
| | | Below pan | 5.6 | 185 | 95 | 86 | 2 |
| 8 | Field corn | Above pan | 5.3 | 205 | 95 | 224 | 2 |
| | | In pan | 5.0 | 170 | 33 | 168 | 2 |
| | | Below pan | 4.9 | 170 | 37 | 192 | 2 |
| 9 | Field corn | Above pan | 6.0 | 392 | 185 | 72 | 2 |
| | | In pan | 6.1 | 132 | 170 | 60 | 26 |
| | | Below pan* | --- | --- | --- | --- | --- |
| 10 | Field corn | Above pan | 4.7 | 240 | 34 | 212 | 12 |
| | | In pan | 4.8 | 150 | 26 | 106 | 10 |
| | | Below pan* | --- | --- | --- | --- | --- |
| 11 | Bermudagrass | Above pan | 5.4 | 116 | 13 | 32 | 14 |
| | | In pan | 5.7 | 185 | 13 | 36 | 2 |
| | | Below pan | 5.1 | 170 | 13 | 22 | 2 |

Table 27 -- Continued

| Site no. | Crop | Sample location | Soil reaction | Acid ammonium acetate extractable | | | |
|--------------------------|----------------------|-----------------|---------------|-----------------------------------|-----|-----|-----|
| | | | | Ca | Mg | K | P |
| --- pH --- | | | | ---- ppm ---- | | | |
| <u>Orangeburg series</u> | | | | | | | |
| 13 | Field corn | Above pan | 5.3 | 185 | 20 | 298 | 2 |
| | | In pan | 4.9 | 104 | 11 | 32 | 4 |
| | | Below pan* | --- | --- | --- | --- | --- |
| 14 | Field corn | Above pan | 4.7 | 91 | 10 | 102 | 4 |
| | | In pan | 4.9 | 61 | 10 | 34 | 2 |
| | | Below pan | 4.8 | 61 | 10 | 46 | 2 |
| <u>Lakeland series</u> | | | | | | | |
| 15 | Pensacola bahiagrass | Above pan | 6.7 | 554 | 77 | 32 | 14 |
| | | In pan | 6.7 | 465 | 30 | 24 | 2 |
| | | Below pan | 5.6 | 104 | 30 | 24 | 2 |
| 16 | Field corn | Above pan | 5.6 | 116 | 5 | 18 | 12 |
| | | In pan | 5.2 | 46 | 3 | 12 | 2 |
| | | Below pan | 5.7 | 46 | 3 | 14 | 2 |
| 17 | Bermudagrass | Above pan | 6.0 | 132 | 8 | 52 | 4 |
| | | In pan | 5.9 | 71 | 3 | 32 | 2 |
| | | Below pan | 5.7 | 61 | 3 | 28 | 2 |
| 18 | Pensacola bahiagrass | Above pan | 5.9 | 150 | 26 | 36 | 4 |
| | | In pan | 6.0 | 91 | 16 | 24 | 2 |
| | | Below pan | 6.1 | 71 | 16 | 30 | 2 |
| 19 | Soybeans | Above pan | 5.3 | 205 | 8 | 84 | 12 |
| | | In pan | 5.3 | 185 | 20 | 92 | 4 |
| | | Below pan* | --- | --- | --- | --- | --- |

* Not sampled since roots were not found below the pan.

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BIOGRAPHICAL SKETCH

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This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

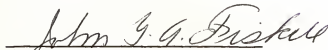
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